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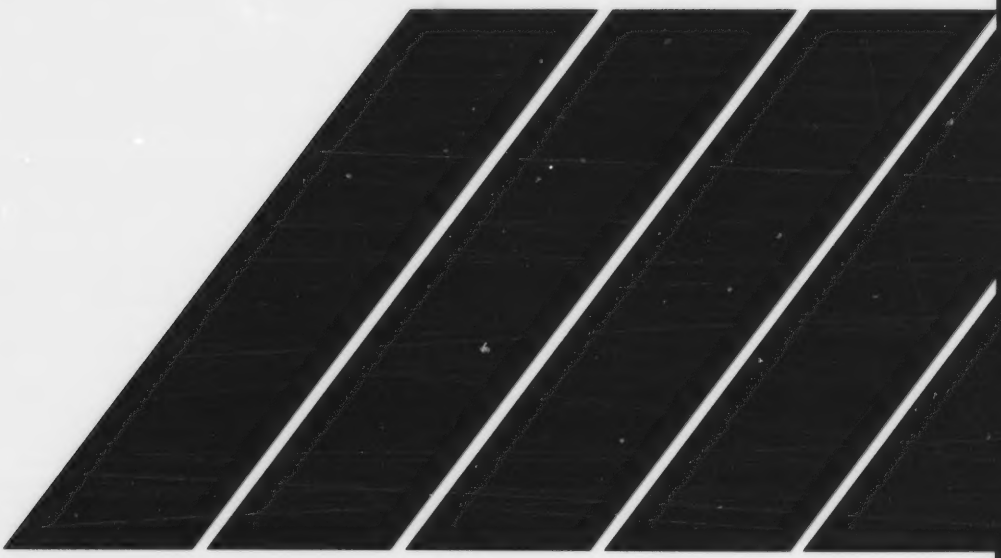

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A STUDY OF THE MERITS AND DIFFICULTIES OF COUPLING A SOFTWOOD SAWMILL AND AND ETHANOL PLANT

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SUMMARY

Softwood sawmills produce wood residues in excess of that required for their own energy needs that are incinerated or landfilled. A potential use for this wood waste is as a feedstock for the production of ethanol. The ethanol produced could be used as an additive for motor gasoline or as an industrial grade product.

In this study, the potential for implementing an ethanol production plant at or near a B.C. interior softwood sawmill was investigated. The study examined:

- a comparison of the merits and difficulties of producing ethanol from wood via acid hydrolysis and enzymatic hydrolysis

- the option of either coupling the ethanol plant to an existing mill, or operating it on a stand-alone basis

- the potential tie-ins of process energy and labour which could benefit (or hamper) the operations of the plants

Two methods exist for the conversion of wood for ethanol: acid hydrolysis and enzymatic hydrolysis. Both involve the hydrolysis (breakdown) of wood into its component sugars, which are then fermented to ethanol and concentrated by distillation to a final product. A study of the current technology shows that acid hydrolysis is considered to be essentially proven technology, while enzymatic is emerging technology. Enzymatic hydrolysis, however, has greater commercial potential in the future because some of the by-products are of higher value.

For the purpose of comparing the two processes, BIOSIM, a previously developed computer simulation program, was used to calculate material and energy balances and estimate capital and operating costs for a number of cases. Simulations were run for both acid and enzymatic hydrolysis scenarios, and each at three

production capacities, chosen to reflect typical B.C. sawmill sizes. The feedstock used was balsam fir, which is representative of B.C. interior softwoods, in the form of sawdust and planer shavings. The results of the simulations were used to analyze the economics for each plant, including schedules of cash flow, revenues, expenses and taxes, and indicators of profitability. A summary of the simulation data is shown in Table S-1.

It was found that acid hydrolysis plants yielded a higher rate of return on investment than enzymatic plants, despite the lower overall yield of ethanol per unit of wood. The sensitivity of the economics to by-product credits, capital costs variations, feedstock price and ethanol selling price were investigated for various cases. The economics of the enzymatic hydrolysis process were found to be quite sensitive to credits for by-products. An increase in the by-product prices can significantly improve the rate of return for this process.

Also included in the study was a survey of a number of sawmill company representatives in both B.C. and Ontario, to gather their opinions on the feasibility of ethanol production, the marketing of ethanol and its by-products, and any technological uncertainties and operation considerations.

In general, the sawmill companies were not interested in the production of ethanol from wood, citing such reasons as:

- too high a demand for wood fibre at the present time to warrant its use for ethanol production

- high capital investment

TABLE S-1 SUMMARY OF SIMULATION AND ECONOMIC DATA FOR THE ETHANOL PLANTS

	ACID HYDROLYSIS			ENZYMATIC HYDROLYSIS		
Ethanol Produced (ML/yr)	9.6	24	48	9.6	24	48
Ethanol Yield (L/ODt wood)	240	240	240	286	286	286
Capital Cost (millions $)	21.5	36.96	56.25	30.84	53.83	80.97
Annual Costs (millions $)	3.38	5.92	9.60	5.22	9.86	17.12
Annual Revenue (millions $)	5.62	14.04	28.09	7.04	17.60	35.20
Internal Rate of Return (%)	9.5	19.6	26.9	4.0	14.1	20.4

- concern about the change in the level of expertise of personnel required for implementation of an ethanol plant

- difficulties in marketing chemical or petrochemical products

Most of the sawmill companies felt that they would first like to see a successfully operating commercial scale ethanol plant before they would consider coupling an ethanol plant to their operation. Construction of an independent, centralized ethanol plant which would purchase wood residues from a number of sawmills was viewed by some as a better option.

RÉSUMÉ

Les moulins à bois tendres produisent de déchets de bois qu'il ne leur en faut pour satisfaire à leurs besoins en énergie. Les surplus de déchets sont incinérés ou mis en décharge. Ils pourraient toutefois servir, entre autres, de charge d'alimentation pour la production d'éthanol, lequel pourrait être utilisé comme additif dans l'essence automobile ou comme produit de qualité industrielle.

Le présent rapport étudie la possibilité de mettre en exploitation une usine de production d'éthanol à même un moulin à bois tendres de l'intérieur de la Colombie-Britannique ou à proximité d'un tel moulin. L'étude comporte:

- une comparaison des mérites et des désavantages de la production d'éthanol à partir de déchets de bois par hydrolyse à l'acide ou par hydrolyse enzymatique;

- une évaluation de deux possibilités, à savoir le jumelage de l'usine à un moulin existant ou son exploitation de façon autonome;

- un examen des possibilités d'économie d'énergie et de main-d'oeuvre pouvant profiter (ou non) aux deux usines.

Il existe deux procédés permettant de convertir le bois en éthanol : l'hydrolyse à l'acide et l'hydrolyse enzymatique. Dans les deux cas, le bois est décomposé par hydrolyse (fragmentation) en sucres qu'on laisse fermenter jusqu'à ce qu'ils deviennent de l'éthanol et que l'on concentre ensuite pour obtenir le produit final. Une étude de la technologie utilisée à l'heure actuelle rélève que l'hydrolyse à l'acide est considérée comme une technique éprouvée et l'hydrolyse enzymatique, comme une nouvelle technique. Cette dernière, toutefois, est plus prometteuse sur le plan commercial étant donné les sous-produits de plus grande valeur qui en résultent.

Afin de comparer les deux procédés, on s'est servi d'un programme de simulation par ordinateur existant, le BIOSIM, pour calculer le bilan énergétique et le bilan des matériaux et estimer les coûts des investissements et d'exploitation de divers scénarios. On a effectué des simulations pour chacun des procédés en utilisant trois capacités de production différentes reflétant bien la taille des moulins types de la Colombie-Britannique. On a utilisé des sciures et des particules de rabotage de sapin baumier comme charge d'alimentation, cet arbre étant représantatif de la famille des bois tendres de l'intérieur de la province. Les résultats des simulations ont servi à analyser les aspects économiques de chaque usine, y compris les prévisions de trésorerie, de recettes, de dépenses et d'impôts ainsi que les indicateurs de rentabilité. Un sommaire des donnés figure au

tableau S-1.

TABLEAU S-1 SOMMAIRE - DONNÉES DES SIMULATIONS ET DONNÉES ÉCONOMIQUES DES USINES DE PRODUCTION D'ÉTHANOL

	HYDROLYSE A L'ACIDE			HYDROLYSE ENZYMATIQUE		
Éthanol produit (ML/an)	9.6	24	48	9.6	24	48
Rendement (L/tonne anhydre de bois)	240	240	240	286	286	286
Coûts des investissements (en millions de $)	21.5	36.96	56.25	30.84	53.83	80.97
Coûts annuels (en millions de $)	3.38	5.92	9.60	5.22	9.86	17.12
Recettes annuelles (en millions de $)	5.62	14.04	28.09	7.04	17.60	35.20
Taux de rendement interne (en %)	9.5	19.6	26.9	4.0	14.1	20.4

Les expériences ont révélé que les usines utilisant le procédé d'hydrolyse à l'acide ont un meilleur taux de rendement des investissements que les autres, même si elles offrent un moins bon rendement général d'éthanol par unité de bois. On a étudié la sensibilité des aspects économiques des divers scénarios aux variations des coûts des investissements, aux prix des sous-produits et de la charge d'alimentation ainsi qu'au prix de vente de l'éthanol. Il semble que, sur le plan économique, le procédé d'hydrolyse enzymatique soit très sensible aux prix des sous-produits. Une augmentation de ces derniers peut considérablement améliorer le taux de rendement du procédé.

Le rapport comporte aussi un sondage mené auprès de représentants de divers moulins en Colombie-Britannique et en Ontario afin d'obtenir leur opinion quant à la faisabilité d'un projet de production d'éthanol, de connaître leur avis au sujet de la commercialisation de l'éthanol et de ses sous-produits et de voir s'ils ont des réserves quant aux aspects technologiques et à l'exploitation d'un tel projet.

De façon générale, les répondants on indiqué qu'ils n'étaient pas intéressés à produire de l'éthanol à partir de bois, évoquant des raisons comme celles-ci :

- demande de fibre de bois trop forte en ce moment pour justifier l'utilisation des déchets de bois aux fins de la production d'éthanol;
- investissement important;
- réserves au sujet des changements quant au niveau de compétence du personnel requis pour la mise en exploitation d'une usine de production d'éthanol;
- difficultés quant à la commercialisation de produits chimiques et pétrochimiques.

La plupart des moulins à bois ont indiqué qu'ils aimeraient voir une usine de production d'éthanol bien fonctionner à une échelle commerciale avant d'envisager la possibilité de jumeler une telle installation à leur exploitation. Certains croient qu'il vaudrait mieux construire une usine indépendante centralisée qui achèterait les déchets de bois de divers moulins.

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NOMENCLATURE

BDU	Bone Dry Unit (BDU of pulp chips weigh 2400 lbs when oven dry)
°C	Degree celsius
GJ	Giga joule (1×10^9)
h	Hour
H - P	High-pressure
IU	International filter paper unit
kg	Kilogram
KL/yr	Thousands of litres per year
kPa	Kilo pascal
kWh	Kilowatt hour of energy
L	Litre
lb	Pound
L-P	Low-pressure
m^3	Cubic meter
ML/yr	Millions of litres/year
M fbm	Thousands of board feet
MM fbm	Millions of board feet
OD kg	Oven dry kilograms
ODt	Oven dry tonnes
ROI	Return on investment
t	Tonne
vol %	Percent by volume
wt %	Percent by weight
$	Dollar

I. INTRODUCTION

A. Background

In recent years there has been continued interest in the production of liquid fuels from renewable resources. Of these liquid fuels, ethanol has been widely used as a fuel additive. The conventional feedstocks for ethanol production have been largely agricultural (mainly corn), but in Canada, an attractive potential feedstock would seem to be forest industry residues. These wood residues are both more economical and more readily available than grain.

Wood residues from sawmills are in excess of that required for their own energy needs. Softwood sawmills common to the interior of B.C produce chips and clean residues which would be suitable for ethanol production. However, the demand for chips by pulp mills is too high to warrant their use in new technology such as ethanol production. The logical feedstock then, is off-specification chips, sawdust and planer shavings, which are often landfilled, incinerated or burned as fuel. The use of these residues could help to alleviate disposal and/or pollution problems and diversify the market of the sawmill.

There are presently two methods available for producing ethanol from wood: acid hydrolysis and enzymatic hydrolysis. Extensive research has been done on both processes worldwide, but there are presently no commercial-scale ethanol-from-wood plants operating or planned for North America.

B. Scope of Work

In this study, the potential for implementing an ethanol plant at a sawmill was explored. The specific objectives of the work were:

- to determine improvements in energy use and feedstock utilization and the potential for shared use of common equipment when an ethanol plant is coupled to a softwood sawmill;

- to identify process and energy tie-ins between an ethanol plant and a sawmill;

- to determine whether an acid hydrolysis or an enzymatic hydrolysis plant is the best option for combining with a sawmill;

- to survey sawmill companies and summarize their concerns with regard to sawmill operations, feasibility of interconnecting an ethanol plant and a sawmill, ethanol production processes, marketing of the various products that would result, and technological uncertainties that would have to be resolved for them to consider building an ethanol plant;

- to identify a sawmill/ethanol plant combination which offers particular process and cost benefits and is worthy of a detailed cost analysis to determine the cost of ethanol production.

To meet these objectives a number of ethanol plant/sawmill combinations were simulated for both acid and enzymatic hydrolysis. Simulation was performed using BIOSIM, a previously developed computer program which generates material flow rates and capital and operating costs for bioenergy systems fueled with wood and wood/bark mixtures. Using this mass and energy balance and cost data, economic analyses were conducted to assess the profitability of the various production configurations.

II. SAWMILL RESIDUES

A. Types and Yields of Residues

The primary product in most sawmills is structural lumber, with pulp chips being produced as a valuable by-product. Residual wood streams are commonly referred to as hog fuel, and include sawdust, planer shavings, chip fines and bark.

While sawmills have been known to produce large quantities of residues, the nature and amount of these residues are inherent to the process. The relevant factors include the type of mill, its major product, the strictness of the requirements for the finished product, the sawing technology, and the kerf of the saw. The availability of wood residues can be seasonal, varying with the demand for lumber. As well, because larger sawmills are often part of an integrated complex, the residues are in demand for use as fuel, alternate wood products, or other uses. Smaller mills, on the other hand, may find it impractical to sell their residues due to low volume or transport distance, opting instead to dispose of them by incineration or landfilling.

Figure II-1 (Levelton and Elliott, 1983) shows a flow sheet for a softwood sawmill which is representative of the B.C. central interior. A range is shown for the quantity of each type of residue generated which reflects the variability in sawmilling equipment used, diameter of the roundwood and other factors.

For this study, material balances were calculated for B.C. central interior sawmills having three nominal lumber capacities: 50, 100 and 150 million board feet (MMfbm) per year (118,000, 236,000 and 345,000 m^3 per year[1]). Forintek, 1985 has published statistics for western tree species and estimates of residue

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[1]Conversion factors based on nominal sizes. Normally, for lumber sold in metric units, volume in m^3 is based on actual sizes, and conversion factors vary by lumber size (Forintek, 1985)

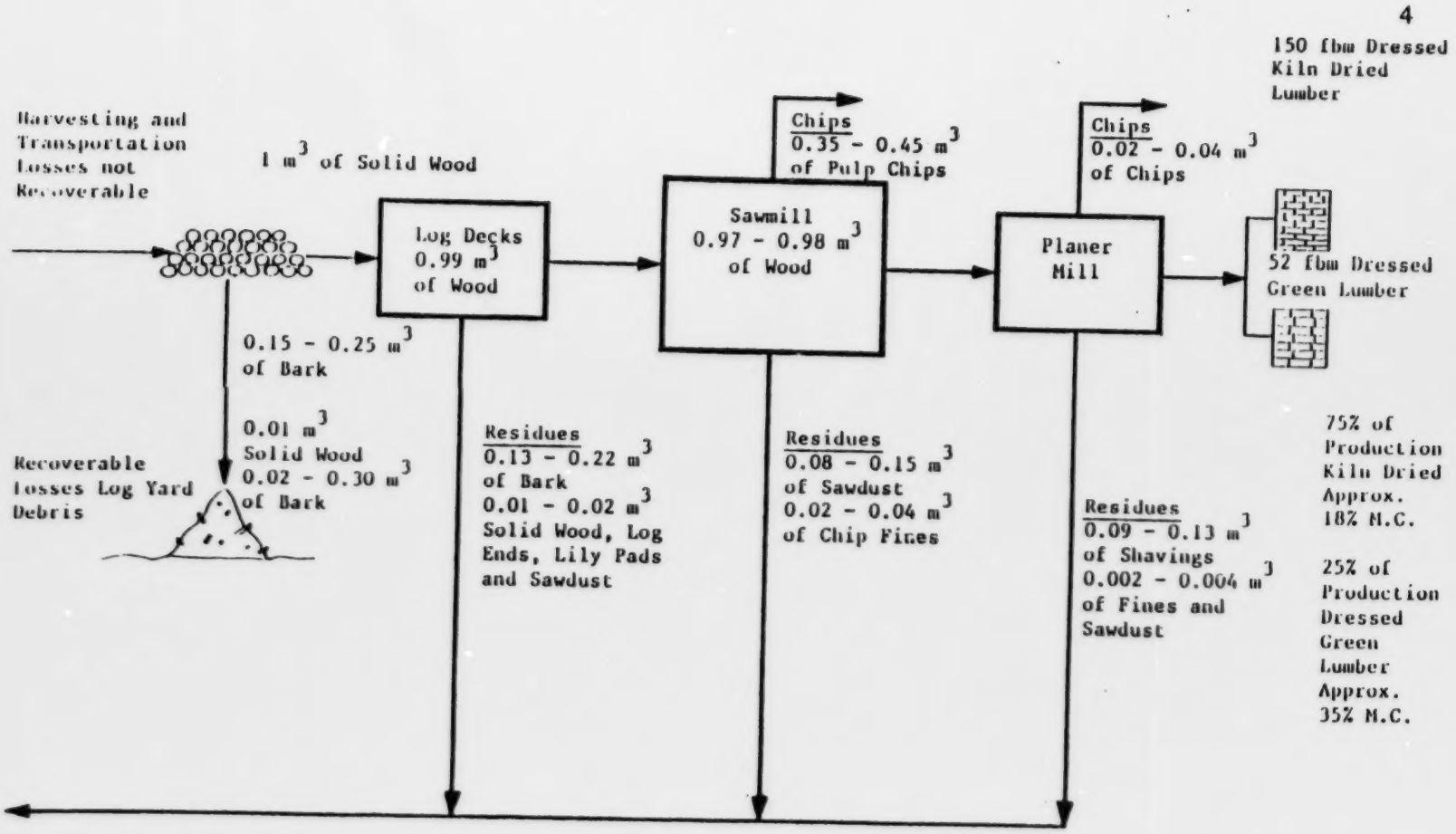
Harvesting and Transportation Losses not Recoverable
1 m3 of Solid Wood
Log Decks 0.99 m3 of Wood
Chips 0.35 - 0.45 m3 of Pulp Chips
Sawmill 0.97 - 0.98 m3 of Wood
Chips 0.02 - 0.04 m3 of Chips
Planer Mill
150 fbm Dressed Kiln Dried Lumber
52 fbm Dressed Green Lumber
0.15 - 0.25 m3 of Bark
0.01 m3 Solid Wood
0.02 - 0.30 m3 of Bark
Recoverable Losses Log Yard Debris
Residues 0.13 - 0.22 m3 of Bark 0.01 - 0.02 m3 Solid Wood, Log Ends, Lily Pads and Sawdust
Residues 0.08 - 0.15 m3 of Sawdust 0.02 - 0.04 m3 of Chip Fines
Residues 0.09 - 0.13 m3 of Shavings 0.002 - 0.004 m3 of Fines and Sawdust
75% of Production Kiln Dried Approx. 18% M.C.
25% of Production Dressed Green Lumber Approx. 35% M.C.

FIGURE II-1 TYPICAL WESTERN SOFTWOOD SAWMILL RESIDUES FLOW SHEET FOR 1 m^3 OF SOLID WOOD THROUGH THE PROCESS

yields for B.C. mill types. Weight average values were derived from these tabulations, and used to estimate the equivalent volumes of solid wood (in m^3) for the three mill sizes. Key assumptions included:

- a typical proportion of 75% : 25% kiln dried to green dressed lumber;
- the bulk of lumber produced was 2 x 4's.

From the wood volumes, the volumes of produced chips, sawdust, shavings and bark were calculated (Figure II-2 and Table II-1). These residue volumes may not be applicable to B.C. coastal sawmills, because of differences in log size, mill equipment and other factors.

B. Alternate Uses of Residues

The residual wood streams from sawmills can provide raw materials for various products, including steam, electricity, pulp and paper, panel products, furniture and horticultural or agricultural products.

Where markets for the wood residues do not exist, disposal creates a problem. Beehive burners are common in sawmills and plywood mills in areas where residue burning is permitted, but present an air pollution problem. Where waste burning is not permitted, landfilling is common, but also poses an environmental problem because chemicals are leached from the wood into the groundwater. Furthermore, both methods of disposal represent a cost to the industry. Thus, the use of wood residues as raw materials for other products would eliminate disposal costs, and often result in a net positive (although small) return.

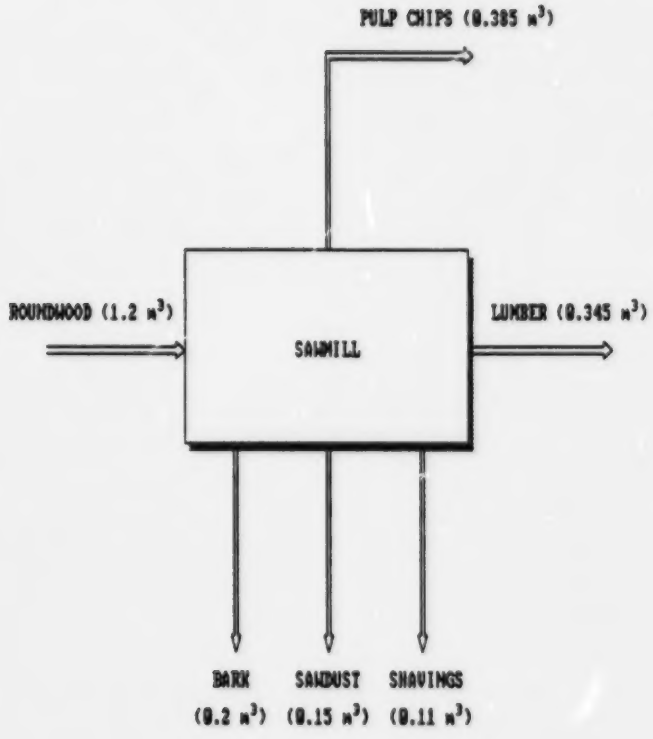

FIGURE II-2 SAWMILL MATERIAL BALANCE

TABLE II-1 MATERIAL BALANCE FOR WESTERN INTERIOR SOFTWOOD SAWMILL

NOMINAL LUMBER PRODUCTION	SOLID WOOD TO MILL		BY-PRODUCTS/RESIDUES GENERATED								
				CHIPS		SHAVINGS		SAWDUST		BARK	
MMfbm/year	m^3/year	10^3m^3[a]	10^3ODt[b]	10^3m^3	10^3ODt	10^3m^3	10^3ODt	10^3m^3	10^3ODt	10^3m^3	10^3ODt
50	118,000	255	95.9	98	36.8	28	10.5	38	14.3	51	24.0
100	236,000	510	191.8	196	73.7	56	21.1	77	29.0	102	48.0
150	354,000	755	283.9	291	110.9	83	31.6	115	43.2	151	71.1

[a] Green volume

[b] Average densities: wood - 376 ODkg/m3 (green)
bark - 471 ODkg/m^3 (green)

1. Production of Energy from Wood Residues

Thermal energy is needed at sawmills for drying lumber and space heating. The energy requirement has been reported to be about 1.6 GJ/Mfbm (thousand board feet) (0.68 GJ/m^3) of lumber produced (Edwards, 1987). Natural gas is frequently a preferred fuel for supplying this heat load due to ease of use, reliability of supply, and low capital cost of burner equipment. However, most sawmill operations generate more than enough wood residues to meet the thermal energy demand for wood drying and space heating. The availability of these residues, combined with the concerns about the potential for increases in natural gas prices, the increasing cost of environmentally acceptable wood residue disposal, and general improvements in wood energy system design, has led to increased use of wood residues for energy. These energy uses include not only lumber drying and space heating, but also generation of steam and electricity and production of solid fuels.

Kiln drying of softwood is a logical and well proven application for wood residues. The conversion from fossil fuel-fired systems to wood-fired systems is often economically attractive, but depends on site specific parameters. The most popular wood-fired kiln drying systems are:

- boiler with steam heating;
- fixed bed combustor with oil heating circuit.

Cogeneration of steam and electricity for mill use and/or sale of electricity is another potential use of wood residues which is receiving considerable interest in the B.C. Interior. Steam is used to satisfy the process heat demand, and also to drive a steam turbine, generating electricity for plant use and sale. The viability of such a system for sawmills, which tend not to have

a large steam or electricity demand, depends largely on the buy-back rate for electricity.

Another use of wood residues is the production of solid fuels. Wood residues as-produced have a variable moisture content, a low bulk density and are prone to handling problems (Levelton and Elliott, 1983). These parameters can be improved by converting the wood residues to fuel products such as logs, briquettes and pellets via densification. Logs and briquettes can be marketed primarily for domestic use in fireplaces and barbecues, respectively. Only pellets are currently marketable as boiler fuel, and are compatible with existing solid fuel handling systems.

2. Non-Energy Uses of Wood Residues

Bark, sawdust and shavings, and chips have a number of alternate uses which are not energy related.

While bark is usually burned as fuel, its market in horticulture and agriculture is expanding, with use in mulching, composting, soil amendment and animal bedding. Bark can also be used as: absorbing agents for oil spills; charcoal; chemicals; additives to well drilling muds; fireplace logs; extractives and medicines; extenders and fillers for plastics; ground cover; composite panelboard; insulation material; and plant growing medium.

The main non-energy use for sawdust and shavings is in composite panelboards such as particle board, insulation board, hardboard and medium density fibreboard. However, the use of sawdust and shavings in pulping is increasing. Other uses for sawdust and shavings include animal bedding and litter, mulch and soil conditioner, packing, thermal insulation, sweeping compounds and porous brick and tile.

C. Residues Available for Ethanol Production

The choice of the wood feedstock to be used for ethanol production will normally depend on the availability, cost, composition and suitability of the various residues. For all near-commercial acid hydrolysis processes, the wood feed must be in sizes ranging from sawdust to chips, be free of dirt to reduce wear of valves, pumps and piping, and have a low bark content. Ideally, the feed size should be comparable in size to that of pulp chips.

In practice, however, chips may not be an economical choice. As a by-product of lumber production, chips can be profitably sold by sawmills to pulp and paper mills. With the current strong market for pulp there is extensive activity in the pulp and paper industry to expand mill capacity. Consequently, pulp chips from sawmills are of high value, typically $ 80/bone dry unit (BDU) ($73/ODt) or more.

Preferably, there should be no competition between traditional forest products industries and ethanol producers, with ethanol producers utilizing low grade residual wood materials which are in low demand. Considering the alternate uses and the requirements of ethanol production processes, the logical feedstock is sawdust and planer shavings, off-specification chips and chip fines. Bark is not suitable as a feedstock for ethanol production because tannins derived from the bark have the potential to inhibit the fermentation process and it acts as a dead load on the system. Considering the above, only bark-free feedstocks have been considered in this study, with emphasis on sawdust and shavings.

III. CONCEPTS FOR COUPLING OF AN ETHANOL PLANT TO A SAWMILL

There are two options for the production of ethanol from sawmill residue streams:

1. a dedicated ethanol plant which is tied-in to a specific sawmill on the same site;

2. a stand-alone ethanol plant, purchasing and utilizing the residues of a number of sawmills.

A. Coupled Ethanol Plant

A number of potential benefits exist for the coupling of an ethanol plant to an existing sawmill. The tie-ins between the two are shown in Figure III-1. The sharing of facilities and material and energy streams could be advantageous to both operations:

- excess wood residues, such as sawdust, shavings and chip fines could be supplied to an adjacent ethanol plant with no shipping costs and little additional operating costs, while avoiding the cost of disposal;

- bark which is presently landfilled, incinerated or otherwise disposed of, could be burned with lignin separated in the ethanol production process to produce steam and/or electricity needed by both plants.

The economic benefits of coupling an ethanol plant to a sawmill are clear:

- more efficient use of materials and energy;

- reduction of operating costs through sharing of equipment;

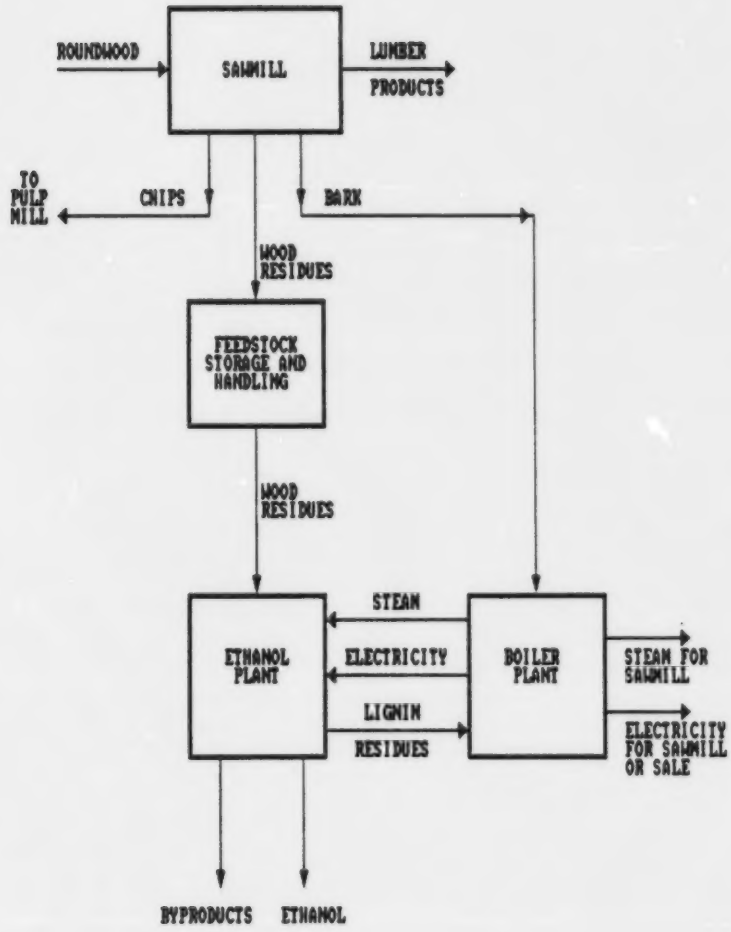

FIGURE III-1 COUPLED ETHANOL PLANT AND SAWMILL

- avoidance of the costs of a feedstock handling and preparation section for the ethanol plant;

- avoidance of the cost of disposal of sawmill wastes.

Moreover, the production of ethanol gives the sawmill the opportunity to diversify its market, although the sale of petrochemicals would be new for sawmill companies in general. A further advantage is that the sawmill can adjust its production mix according to the prevailing market, diverting more or less residues to the ethanol plant as demand and price dictate.

One of the main drawbacks of an ethanol plant/sawmill combination is the lack of experience of sawmill personnel with chemical processes, equipment and marketing. The difference in expertise is a concern of most sawmill companies and will be discussed in more detail in Chapter VII.

Another problem would be in the balancing of the fibre demand of the two plants since sawmills are striving for better utilization of roundwood, and consequently, minimization of the quantities of residues produced. In some existing plants, a large proportion of wood residues are already in use and would not be available for ethanol production.

B. Stand-Alone Ethanol Plant

A stand-alone ethanol plant could be located in the proximity of a number of sawmills, purchasing excess residues from the mills for ethanol production (Figure III-2).

Operation of a stand-alone ethanol plant would eliminate a number of the disadvantages associated with the dedicated ethanol plant described previously.

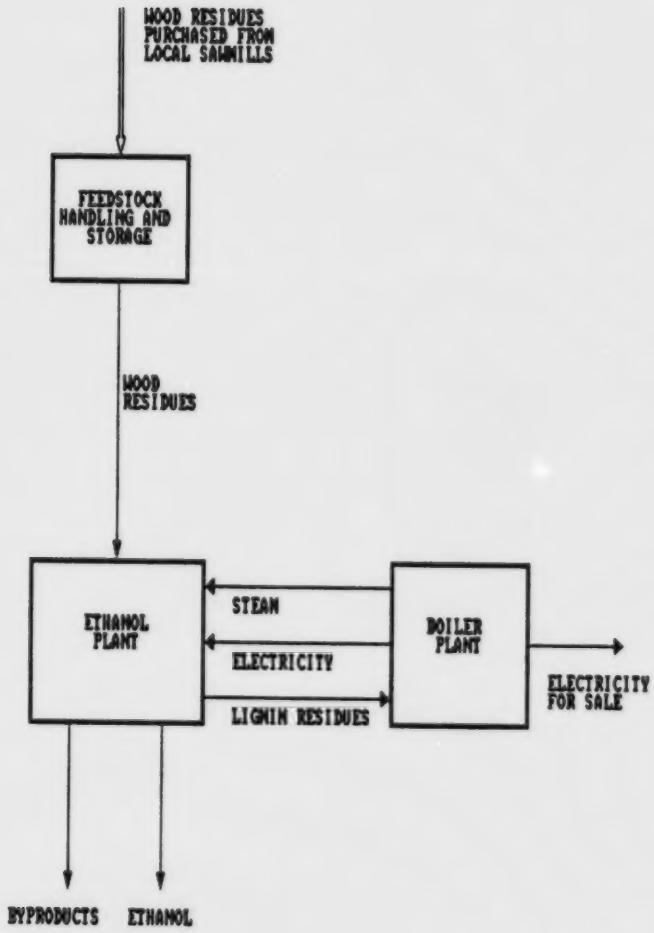

FIGURE III-2 STAND-ALONE ETHANOL PLANT

Firstly, concerns about the expertise of the staff could be avoided since plant management and operating personnel could be selected with background in chemical process industries. The contributing sawmill companies could elect to sell only those residues which are surplus, and retain as much as needed for their own use. Finally, the management of the ethanol plant could concentrate only on ethanol sales and the development of suitable markets.

In general, costs for a stand-alone plant would be higher because there would not be any sharing of the costs associated with the site, equipment or utilities, though results of this study show this is only significant for small plants. As well, additional costs for shipping of residues are incurred. Ideally, the stand-alone plant would be located among a geographic "cluster" of sawmills and pool the resources of those mills. Presumably, the supply of wood residues to the plant would be variable, given the seasonal markets for lumber production, so that a sizeable inventory of feedstock would have to be kept to ensure that steady operation of the ethanol plant could be maintained.

IV. ETHANOL PLANT DESIGN

A. Theory

There are three grades of ethanol which are produced commercially: beverage, industrial and fuel. Fuel grade ethanol has the least stringent specifications regarding purity, and is the grade under consideration in this study.

Ethanol can be produced by synthesis from petroleum feedstocks or by fermenting sugars with yeast. These sugars can be derived from a number of renewable sources, including sugar crops, starch-containing grains (e.g., corn) and lignocellulosic material (such as wood). In North America, most fermentation ethanol is produced from corn. If the technology was fully developed, the use of wood could potentially be a less expensive alternative, since it has no competing value as food.

The conversion of wood to ethanol is controlled by the chemistry of the wood's main components: cellulose, hemicellulose and lignin. Cellulose is a linear homogenous polymer composed of several thousand glucose units, and generally constitutes 41% to 45% of the dry wood weight. Glucose is a 6-carbon sugar which can be fermented to ethanol. Hemicelluloses make up 23% to 30% of the dry wood weight, and they are structurally more complex than cellulose. Hardwoods contain two hemicelluloses, xylan and glucomannan, while softwoods contain galactoglucomannan and xylan. Glucomannan and galactoglucomman are polymers of 6-carbon sugars (hexosans) and xylan is a polymer of 5-carbon sugars (pentosans). Lignin makes up most of the balance of the wood. It is a complex, amorphous, aromatic substance composed of cross-linked polymers of phenyl propane units joined by benzylic and phenolic ether linkages.

Table IV-1 (Levelton and Elliott, 1983) shows the typical composition of several wood species. In general, hardwoods have a higher holocellulose (cellulose and

TABLE IV-1 PERCENTAGE COMPOSITION OF CERTAIN WOODS (Extractive Free, Ash Free)

SPECIES	LIGNIN	HOLO-CELLULOSE	ALPHA-CELLULOSE	HEMI-CELLULOSE	PENTOSANS
Softwoods					
White Spruce	26.6	73.3	49.5	23.8	10.9
Red Spruce	26.6	72.9	48.3	24.6	11.6
Eastern Hemlock	31.5	68.5	48.2	20.3	10.0
Balsam Fir	30.1	69.9	44.0	25.9	10.3
Jack Pine	27.2	72.5	49.5	23.0	12.3
Hardwoods					
Aspen	17.3	82.5	50.7	31.8	23.5
Willow	22.0	78.3			
Maple	23.5	76.3	50.0	26.3	
White Oak	24.1	75.1	49.5	25.9	

hemicellulose) content and a lower lignin content than softwoods, although the total hexosan content is about the same.

The first step in the conversion of wood to ethanol is hydrolysis: the breaking down of cellulose and hemicelluloses into component sugars, which can then be fermented to ethanol. The basic reactions for 6-carbon sugars are:

1. $(C_6H_{10}O_5)n + nH_2O \xrightarrow{\text{hydrolysis}} nC_6H_{12}O_6$
   cellulose → glucose

2. $nC_6H_{12}O_6 \xrightarrow[\text{(with yeast)}]{\text{fermentation}} 2nC_2H_5OH + 2nCO_2$
   glucose → ethanol

Although cellulose, like starch, is a polymer of glucose, it is much more difficult to hydrolyze economically. Cellulose is much less accessible and reactive than starch, because it is intended to provide strength and resistance to microbiological attack in trees. The polymer chains are arranged in a crystalline structure and coated by lignin, which "glues" the polysaccharide molecules together. Consequently, both the lignin and the crystallinity of the matrix must be overcome before hydrolysis is possible. Once the hydrolysis step is accomplished, the fermentation to ethanol and subsequent distillation processes are well established and readily accomplished.

B. Ethanol Production Processes

Conventional ethanol processes include synthesis from petrochemicals and fermentation of starch or sugar plants. The production of ethanol from sugar cane or sugar beets is a relatively simple process, involving only the extraction of the sugars followed by fermentation with yeast. The process is expensive, however, due to the costs of the raw material. A less expensive alternative is ethanol from starch, which occurs in cereal grains and root crops. Starch, like cellulose, is a

polymer of glucose, but is easily hydrolyzed to its sugar monomers. From this point, conventional fermentation and distillation processes are used.

Ethanol can be produced from wood feedstocks by first hydrolyzing the cellulose and hemicelluloses to produce 5-carbon and 6-carbon sugars then fermenting these sugars to produce ethanol. Processes to produce ethanol from wood have been investigated since the early 1900s, including operation of commercial-scale plants in Germany and Switzerland during World War II. Intensive research of hydrolysis and fermentation processes for wood and other biomass feedstocks has been underway around the world since the late 1970s.

A key step in converting wood to ethanol is hydrolysis. This conversion step may be accomplished using either acids or enzymes. Acid hydrolysis can be performed using dilute acid solutions, strong acid solutions, or gaseous acids. Only hydrolysis with dilute sulphuric acid, typically at concentrations of 0.4% to 0.6%, can be considered as commercial technology. However, this technology has not been applied at a commercial scale for producing ethanol from wood since the late 1940s, except for a 30,000 L/day plant constructed in Brazil for Coque E Alcool da Madiera S/A (Coalbra) with technical assistance from the U.S.S.R. Commissioning of the plant was to take place in 1983, with operation at rated capacity to be achieved by early 1984. An update on the status of this plant was not available for this study. Enzymatic hydrolysis is being developed using cellulolytic organisms that synthesize cellulases, which break down cellulose into sugars. Much research has been done to develop more efficient enzymatic hydrolysis processes and to reduce the processing time needed. Compared to acid hydrolysis, enzymatic hydrolysis offers the potential for increased sugar yield, less degradation of lignin, operation at low pressures and temperatures and use of non-corrosive process fluids.

The strengths and weaknesses of dilute acid hydrolysis and enzymatic hydrolysis are summarized in Table IV-2. Research in enzymatic hydrolysis has helped to increase yield and reduce processing time. Pilot tests of enzyme production for prolonged periods have been completed successfully, resolving some of the identified weaknesses.

This study examined both dilute acid hydrolysis and enzymatic hydrolysis based plants for producing ethanol from wood. The yields considered for these plants were determined from a review of the literature and consideration of the likely performance that could be achieved in a commercial plant. The impacts of improvements in hydrolysis or other technologies used in the ethanol plant can be seen from some of the results of the sensitivity analysis discussed in Chapter VI.

C. Acid Hydrolysis Processes

1. Background

Acid hydrolysis technology has been under development since the early 1900s. At present, the two principal acid hydrolysis catalysts are:

- concentrated sulfuric acid at low temperature;
- dilute sulfuric acid at high temperature.

Concentrated sulfuric acid processes operate near ambient temperature, so that produced glucose, which is sensitive to temperature, is less likely to degrade. Although glucose yields for concentrated acid systems are potentially higher (reaching 90% of theory (Levelton & Elliott, 1983)), these systems have problems with acid recovery and equipment corrosion.

TABLE IV-2 FEATURES OF GENERIC HYDROLYSIS PROCESSES

DILUTE ACID HYDROLYSIS	ENZYMATIC HYDROLYSIS
Strength:	
- commercial technology - relatively fast conversion process - suitable for hardwoods and softwoods - performance data well documented - moderate sugar yield - potential for continuous process - moderate processing time (3 to 4 hr)	- few undesirable by-products - high sugar yield - low process temperature and pressure - non-corrosive fluids - lignin remains in reactive form - potential for simultaneous saccharification and fermentation
Weakness:	
- batch process - structural collapse of hardwoods upon hydrolysis causes flow problems - low sugar concentration - undesirable by-products - corrosive fluids - requires neutralization and disposal of acid hydrolyzate	- slow conversion process (24 h) - hazard of contamination by foreign organism - expensive enzymes - requires pretreatment to make cellulose available to enzyme - requires enzyme recovery and processing - pilot/experimental technology - inhibition of enzyme activity by hydrolysis products

Dilute acid hydrolysis has a long history of development. In the early 1900s and during World War I, two dilute sulfuric acid plants were in operation in the southern U.S.A, with net overall yields of about 92 litres of product per oven-dried tonne of wood. During the 1920s, Heinrich Scholler of Germany developed the Scholler process, which improved alcohol yields to 217 to 242 litres per tonne of dry wood. The process involves the addition of successive batches of hot sulfuric acid at 0.8% concentration to a wood charge, and withdrawal of sugars as they are formed, thereby lessening sugar degradation and improving yields. Toward the end of World War II, the U.S. Forest Products Laboratory further refined the Scholler Process, developing what is now known as the Madison Process. This process uses continuous addition of acid and continuous removal of the hydrolyzate; the shorter contact times lessen sugar degradation and improve ethanol yields for some feedstocks to upwards of 269 litres/tonne of dry wood.

Considerable pilot scale development was done by the New Zealand Forest Products Research Institute to refine the Madison process for *Radiata Pine*. Yields of this and similar processes have alcohol yields ranging from 240 to 250 litres/oven dried tonne of wood. The process upon which this study is based is the NZ FRI pilot testing of the Madison process.

2. Conceptual Design

The acid hydrolysis plant is designed for use of clean, relatively bark-free sawdust and shavings as the wood feedstock. The wood species is balsam fir, which has a composition that is representative of softwoods in the interior of B.C. The plants considered produce 10, 25 and 50 million litres of anhydrous ethanol (99.5 wt %) per year, which have feed requirements that could be satisfied by softwood sawmills in the interior of B.C. The overall ethanol yield is about 240 litres/dry tonne of wood.

The major reaction routes during hydrolysis for each component are shown in Figure IV-1. Cellulose is hydrolyzed to glucose, with some degradation to HMF (hydroxymethyl-2-furfuraldehyde) and laevulinic acid due to high temperature or prolonged exposure to acid. The hemicellulose components hydrolyze as follows:

pentosan	----> xylose	----> furfural	----> pseudolignin
hexosan	----> glucose (or mannose)	----> HMF	----> laevulinic acid

The hexosan sugars may hydrolyze to glucose or mannose depending on the wood species. The lignin is not hydrolyzed, but forms an unreactive substance which is useful, after dewatering, as fuel.

A simplified flowsheet for the conceptual design of the acid hydrolysis plant is shown in Figure IV-2. For the small ethanol plant (10 million L/yr) feedstock is assumed to be available on site, whereas for the two larger plants, additional feedstock is purchased. Feedstock is processed in the materials handling and storage area before being fed in batch to the hydrolysis section. Here, the wood is preheated with steam prior to acid treatment. Dilute sulfuric acid (0.5% concentration), at temperatures between 150°C and 190°C, is added from the top of the reactor. As hydrolysis proceeds, the hydrolyzate is continuously removed from the reactor bottom. The conversion of wood to sugars is:

- 67.2% conversion of hexosan sugars (i.e., cellulose + hemicellulose hexosan);

- 60.9% conversion of pentosan sugars.

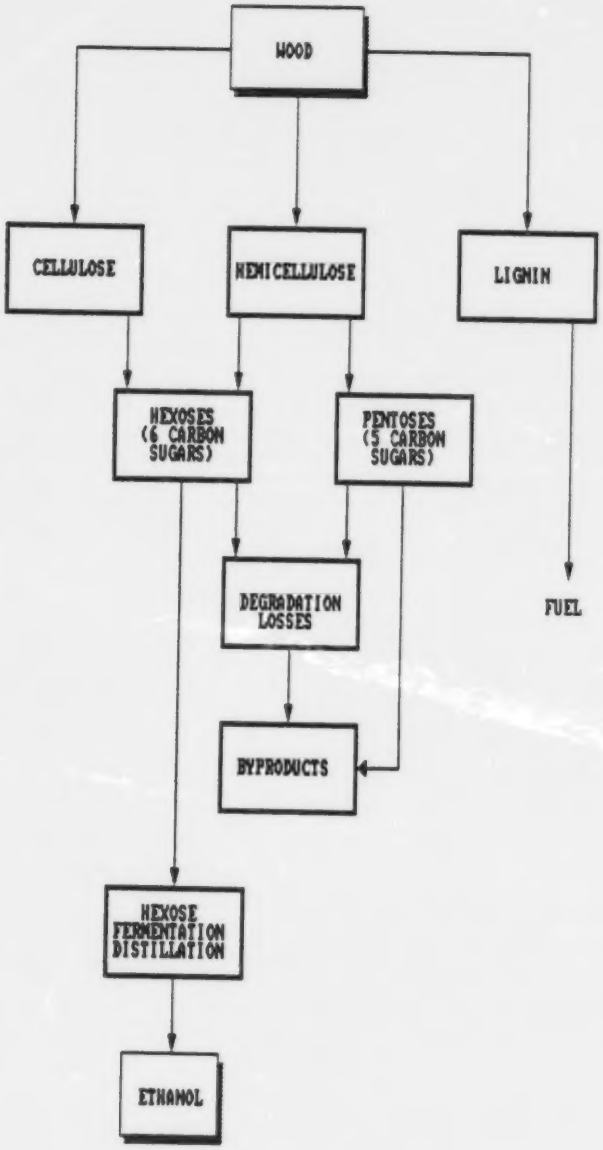

FIGURE IV-1 REACTION ROUTES OF COMPONENTS DURING ACID HYDROLYSIS

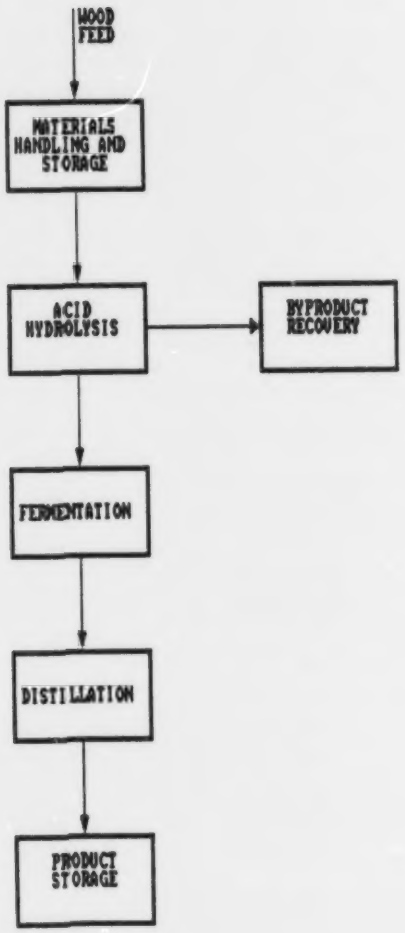

FIGURE IV-2 CONCEPTUAL FLOWSHEET FOR THE ACID HYDROLYSIS PLANT

The hydrolyzate is then neutralized and concentrated before being sent to the fermentation section. The hexose sugars are fermented using yeast, and the resulting dilute ethanol solution is sent to the distillation section. Distillation is azeotropic, producing a final product of 99.5 wt % ethanol in water. The by-products recovered include: unfermented pentose sugars, ligneous residues, recovered yeast from fermentation and furfural. The value and uses of these by-products will be discussed in subsequent sections.

3. Process Design

The design parameters and assumptions used in the design of the acid hydrolysis plant are described below by plant section.

(a) Feedstock Handling and Storage

The feedstock handling and storage section is shown in Figure IV-3. For the small plant (10 million L/yr), sawdust and shavings are conveyed from the sawmill to outdoor storage. For the larger plants (25 and 50 million L/yr) additional biomass is purchased. Purchased feedstock is delivered by truck in large trailers, which are weighed using an automated pitless weigh scale. A platform dumper unloads the trailer contents in a hopper, which discharges into a take-away conveyor. From this point, feedstock handling and storage is common to all three plant sizes. Feed is conveyed to the stacking/reclaiming area, where a stationary belt conveyor piles the wood in outdoor storage and a reciprocating stoker/reclaimer recovers it. A rubber-tired front end loader is kept in reserve to assist as required. Reclaimed wood is conveyed to the foreign materials removal area; ferrous metals, sand and wood fines are removed using an overhead magnet, sand removal screen and deck

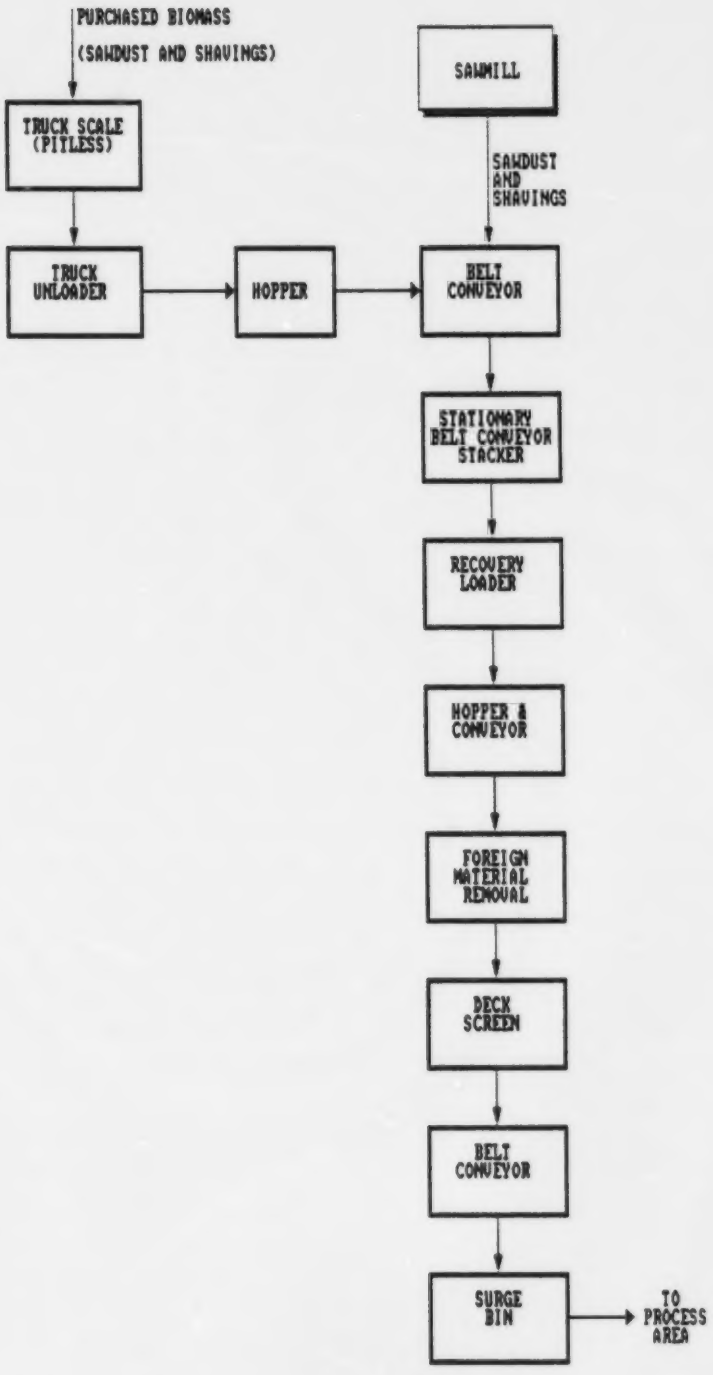

FIGURE IV-3 MATERIALS HANDLING AND STORAGE

screen, respectively. A belt conveyor transports the feedstock to a surge bin designed to hold a 24 hour inventory.

(b) Hydrolysis

The acid hydrolysis plant design is based on that developed by Burton (1982) from pilot tests of the Madison Process on *Radiata pine* feedstock, at the New Zealand Forest Research Institute. The primary unit processes are shown in Figure IV-4. The wood charge is fed into the hydrolyzer in batch mode and heated with live steam (0.45 kg steam/kg dry wood) to a temperature of 140°C to 150°C. Steam pretreating must be carefully controlled with respect to temperature because it can result in hydrolysis of unstable and easily accessible hemicellulose to hexose and pentose sugars and degradation products. Once the preheating is finished, sulfuric acid, at a concentration of 5% by volume (5% H_2SO_4) and a temperature of 190°C, is continuously injected at the top of the reactor and allowed to percolate down through the wood charge. With the addition of the hot acid, the reactor temperature rises from 150°C to 190°C over the course of the four hour batch. The ratio of acid to wood is 0.055 kg acid/kg dry wood. Although the wood is fed in batch, the overall process is "semicontinuous" because the produced hydrolyzate is continuously removed at the bottom of the reactor, maintaining a constant volume. The purpose of this procedure is to obtain as high a yield of fermentable sugars as possible by preventing the degradation of the produced sugars. Glucose yield is sensitive to both residence time and temperature.

The hydrolysis process, from the time a new feed batch is added to the hydrolyzer to the time the ligneous residue is discharged, takes approximately 240 minutes. This time is used to fill the hydrolyzer,

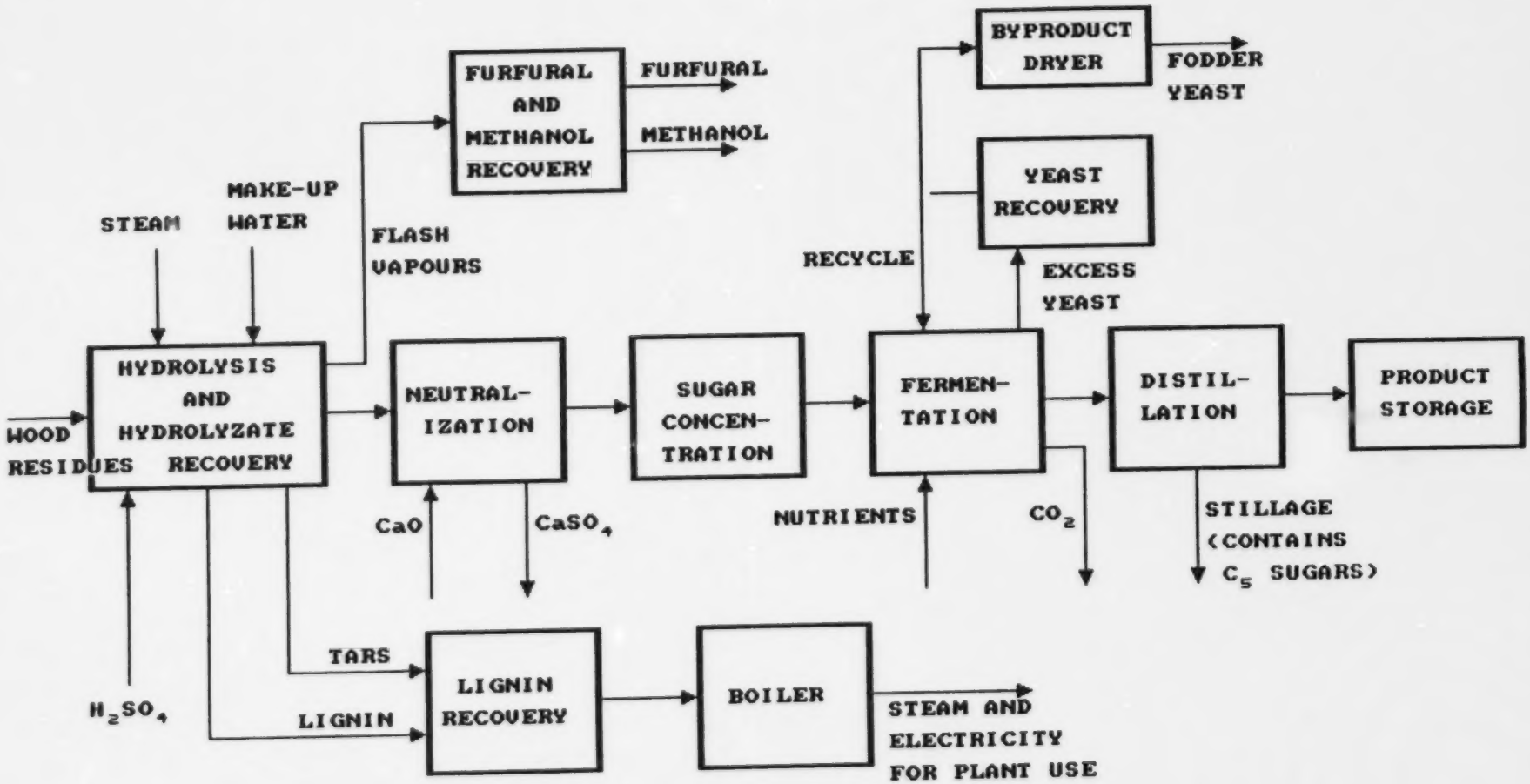

FIGURE IV-4 SIMPLIFIED PROCESS DIAGRAM FOR AN ACID HYDROLYSIS PLANT

heat with steam, inject acid, percolate and discharge the residual hydrolyzate and ligneous residue. The main percolation step lasts for approximately 120 minutes. The time periods are based on past pilot tests and should be considered only as an initial estimate.

The hydrolyzate stream, which contains both hexose and pentose sugars at high temperature and pressure, passes to a two-stage flash cooling unit which flashes some of the water to steam. Any furfural, methanol and HMF produced by sugar degradation are assumed to be carried overhead with the flash vapours. The hydrolyzate is cooled to approximately 100°C and the low pressure steam can be utilized as process steam elsewhere in the plant.

(c) Neutralization

The total sugar concentration in the partially cooled hydrolyzate is about 5 wt%. A 15% slurry of lime (CaO) and water is used to neutralize the acidic hydrolyzate, reacting as follows:

$$CaO\ (slurry) + H_2SO_4 \text{ ----> } CaSO_4\ (precipitate) + H_2O$$

At the elevated temperature of 100°C, the $CaSO_4$ is less soluble and as a consequence, precipitates, facilitating easy removal by centrifuge.

(d) Concentration

The neutralized sugar solution is then sent to a multiple effect evaporator to concentrate the hexose sugars from about 4.6 wt% to 11.0 wt%. By concentrating at this stage, the energy requirements and costs for the final distillation of the ethanol product are substantially reduced.

(e) Fermentation

Ordinary bakers yeast (*Saccharomyces cerevisiae*) after conditioning to wood hydrolyzates, is used to ferment the glucose solution. The fermentor consists of a continuous stirred tank reactor (CSTR) to which the concentrated sugar solution is continuously fed. Diammonium phosphate and urea are added as fermentation nutrients. Hexose ferments as follows:

$$\underset{\text{hexose}}{C_6H_{12}O_6} \longrightarrow \underset{\text{ethanol}}{2C_2H_5OH} + \underset{\text{carbon dioxide}}{2CO_2}$$

Theoretically, the yield of this reaction is 0.51 kg of ethanol and 0.49 kg of carbon dioxide per kg of hexose. However, sugar solutions from acid hydrolysis are very different from conventional starch solutions due to the presence of decomposition products such as furfural, HMF and resinous substances, which have been found to inhibit the fermentation process. Another limiting factor is the ethanol tolerance of the yeast, which cannot grow or produce in solutions containing more than 12% ethanol by volume. To allow for these inefficiencies yields of 0.47 kg of ethanol and 0.5 kg of CO_2 per kg of hexose, i.e., a 92% fermentation efficiency, are assumed.

The fermentation time is seven hours at temperatures maintained between 32°C and 35°C. The produced beer contains 4.9 wt % or 6.1 volume % ethanol in water, which is sent to the distillation section.

Bakers yeast, and other yeasts commonly used to ferment hexose sugars, do not ferment pentose sugars. Extensive research is currently underway to develop and improve microorganisms capable of fermenting

xylose, the principle hemicellulose pentose sugar. The implementation of this technology could improve ethanol yields by as much as one-third.

(f) Yeast Recovery

The ethanol stream from the fermentor contains excess yeast which is recovered by centrifuge, with a portion being recycled to the fermentor and the remainder dried to a moisture content of 10% for use as a by-product. The by-product yeast has a high protein content and could be used as fodder.

(g) Distillation

The fermented beer stream contains a 4.9 wt % concentration of ethanol in water. Azeotropic distillation is used to produce anhydrous ethanol, avoiding phase separation problems associated with hydrous ethanol.

A low energy azeotropic distillation system proposed by Katzen (Klass and Emert, 1981) was used for this study. The product is the anhydrous ethanol, while the stillage contains unfermented pentose sugars, which are assumed to pass unchanged through the distillation process. This stillage is concentrated from 0.9 wt % to 65 wt % pentose sugars for sale as a feed supplement, or possibly for conversion to furfural.

4. Product and By-products

The main product is anhydrous ethanol, which is marketable as either a gasoline extender or octane enhancer.

The main by-products are pentose sugars, furfural, lignin and yeast. Other by-products or wastes include HMF, laevulinic acid, formic acid, gypsum and tars.

Furfural is produced from hemicellulose during both the steam pretreatment and hydrolysis steps as a degradation product of pentose sugars. Furfural is a chemical intermediate used in the production of furfural alcohol and furan resins. It is also used in the lube oil industry and in the production of tetrahydrofuran (THF) and other polymers (Lambert et al, 1989). The hydrolyzer material balance (Figure IV-5) gives the amount of furfural produced per kilogram of dry input wood as 8.4% of the pentosan fraction.

The balance of pentose sugars not degraded to furfural end up in the stillage following distillation. If the economics were favourable, these sugars could be converted to additional furfural. The simplest procedure though, is to concentrate the pentose solution to a 48% syrup, to be sold as animal feed molasses (Stone, 1982). Other options include the fermentation of pentose sugars to ethanol (as discussed earlier), the use of the sugars as a substrate for yeast production, and the anaerobic digestion of the sugars to produce a methane-rich biogas.

Lignin passes through the hydrolysis process with very little loss in weight, but is degraded to an unreactive form which is useful only as a fuel. This lignin can be used to produce steam and/or electricity for plant use or sale,

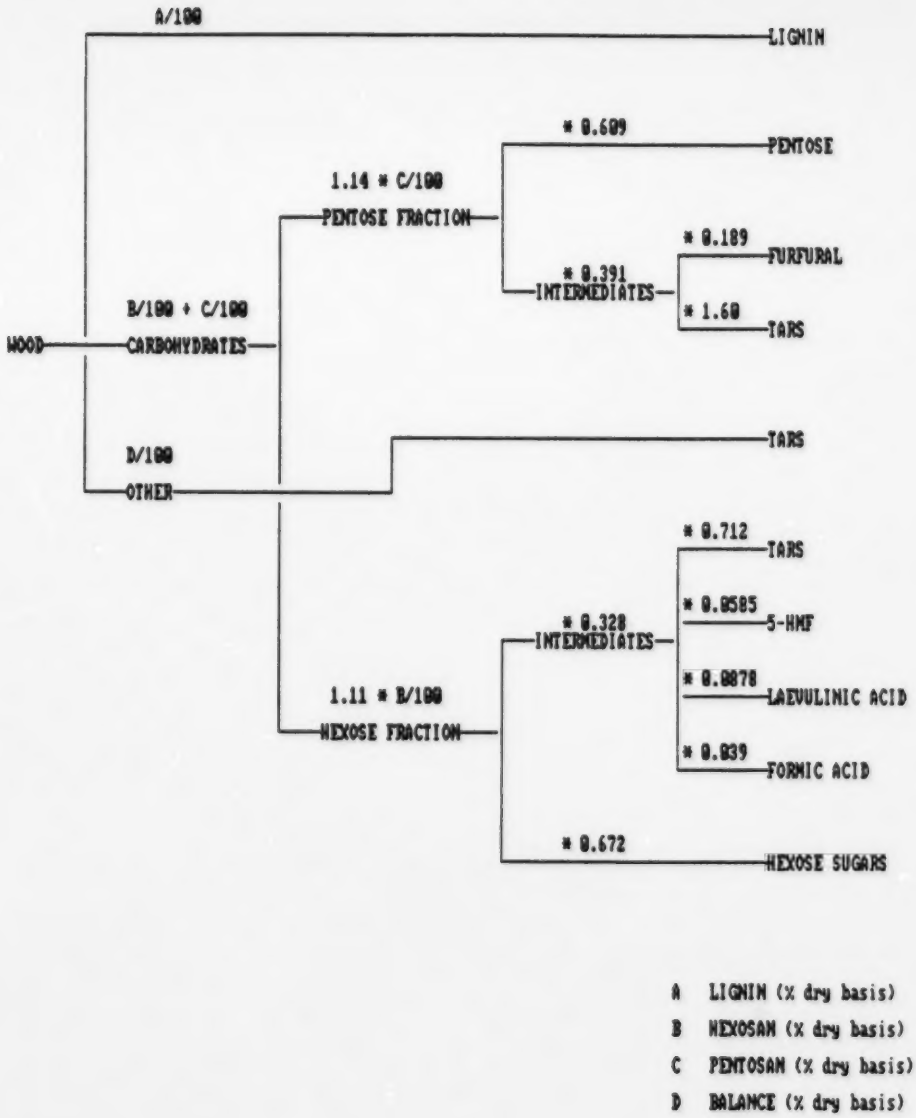

FIGURE IV-5 MATERIAL BALANCE FOR ACID HYDROLYSIS

or can be sold directly as fuel. For this study, lignin from acid hydrolysis is used as boiler fuel to cogenerate steam and electricity for plant use.

Any excess yeast not required for fermentation can be dried to about 10% moisture content and sold as fodder yeast. This by-product is comparable to high protein feeds such as soybean meal.

5. Assessment of the Status of Available Technology

Although there are presently no commercial-scale acid hydrolysis plants in existence outside of the U.S.S.R., the technology is considered proven. The process has been used commercially by Inventa and in a new plant in Brazil operated by Coalbra.

Despite its proven technology, the main drawback of an acid hydrolysis process is the low sugar yield. Ideally, 1000 kg of softwood, which typically contains 45% cellulose, could be hydrolyzed to 500 kg of glucose. This weight of glucose, by stoichiometry, could yield 256 kg, or 320 litres of ethanol. However, Mackie et al, 1982, report that sugar yields greater than 80% of theoretical cannot be achieved by dilute acid hydrolysis. Therefore, the maximum ethanol yield for acid hydrolysis is about 255 L/dry tonne of wood.

Another area of concern is the suitability of sawdust and shavings for the process. The ideal feed is pulp chips, but these are too expensive for use in ethanol production. However, Inventa (Levelton and Elliott, 1983) has used sawdust as a feedstock in their plant and it is assumed that the Madison process could be operated with this feed with a yield near 240 L/dry tonne.

The lignin by-product from acid hydrolysis is in an unreactive form, and as such, is useful only as boiler fuel.

The current research activities in ethanol production from wood by acid hydrolysis include:

- fermentation of xylose and other pentose sugars using yeasts and organisms other than *Saccharomyces cerevisiae*; this technology could greatly improve the ethanol yield;

- two-stage hydrolysis processes (Lambert et al, 1989) with hemicellulose being hydrolyzed and separated in the first stage, and cellulose hydrolyzed in the second, thereby minimizing degradation of the hemicellulose sugars.

D. Ethanol by Enzymatic Hydrolysis Process

1. Background

Enzymatic hydrolysis processes, unlike acid, use enzymes to break down the cellulose polymer to component glucoses. Enzymes are commonly used in hydrolyzing starch and grains to sugars, but have yet to be proven for wood hydrolysis at other than bench-scale.

During the late 1940s, Dr. E. Reese of the U.S. Army Natick Laboratories researched the degradation of cellulose by cellulolytic enzymes. While the original scope of this work involved the prevention of deterioration of cellulose, the emphasis shifted in 1968 to the development of a process to break down cellulose. It was found that the enzyme cellulase would hydrolyze cellulose, and cellulase continues to be the enzyme of choice today. The Natick Labs identified a fungus, *Trichoderma reesei*, which produced a complete cellulase in high quantities.

A complete cellulase is one which contains 3 enzyme components: exo-β-glucanase; endo-β-glucanase; and β-glucosidase or cellobiase. The hydrolysis of cellulosic material depends on the synergistic action of all three enzyme components, each in the proper amount. The endo-β-glucanase acts randomly on the interior of the cellulose chain, generating new chain ends. These chain ends are attacked by the exo-β-glucanase, producing cellobiose, a dimer of two glucose units. Finally, the β-glucosidase splits the cellobiose into glucose units. The mechanism is complicated however, by product inhibition. Both endo- and exo-β-glucanase are inhibited by cellobiose and, to some extent, glucose (Little, 1985), and β-glucosidase is inhibited by glucose. Thus, it is essential that all three enzymes be present in the proper amounts; a deficiency in any one enzyme may inhibit the others, or not provide the necessary substrate for the others to act on.

Much work has been done at a laboratory scale but there are no commercial or near-commercial processes for enzymatic hydrolysis of biomass to sugars.

2. Conceptual Design

The basic enzymatic hydrolysis process for ethanol production can be divided into five principle sections:

- pretreatment of the wood;
- enzyme production;
- hydrolysis;
- fermentation;
- distillation.

These are shown in Figure IV-6.

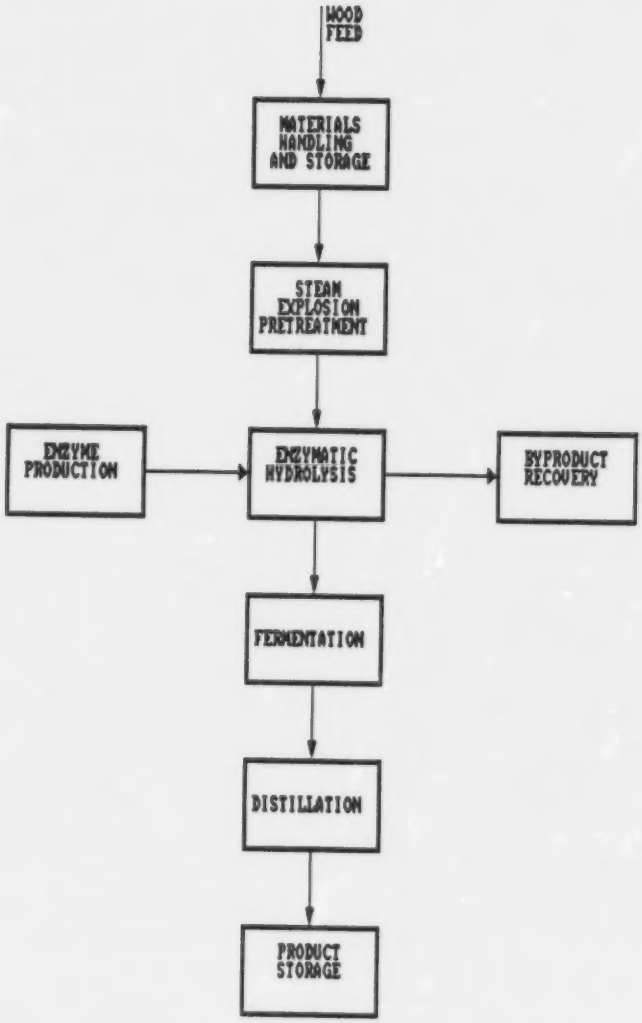

FIGURE IV-6 CONCEPTUAL FLOWSHEET FOR THE ENZYMATIC HYDROLYSIS PLANT

Wood pretreatment is necessary due to the nature of the wood matrix and the size of the enzyme molecules. The cellulose is crystalline in nature, and surrounded by a lignin-hemicellulose sheath, such that the surface area is too small for the large enzyme molecules to access. The enzymes must bind to the surface in order to catalyze the hydrolysis reactions. It is necessary to break down the hemicellulose-lignin matrix, effectively isolating the cellulose and increasing its surface area.

Various methods of pretreatment have been studied, including:

- biological removal of lignin;
- pulverization or other mechanical means;
- alkali;
- sodium chlorite;
- ozone;
- dilute acid prehydrolysis;
- organic solvent pretreatment;
- explosive decompression with steam.

The method chosen for this study was explosive decompression with steam, also known as steam explosion or autohydrolysis. The method involves the heating of the wood charge with steam at high pressures and temperature (typically of the order of 4000 kPa and 250°C) followed by rapid decompression of the charge to low pressure. The high-pressure steaming partially decomposes hemicellulose, which in turn catalyzes the depolymerization of lignin and hemicellulose. The lignin is amenable to selective removal by, for example, solvent extraction, and the cellulose is both sterilized and more accessible to enzymes.

Enzymes are produced by growing a cellulase-producing organism in submerged culture, using a cellulase-inducing carbohydrate as the primary

source of carbon. The carbon source may be cellulose, but in this case, lactate was used. The enzyme production process requires air, various nutrients and an environment free of contamination. The enzyme fermentation requires 2 to 7 days at a temperature of 28°C to 32°C (Little, 1985), and the resulting enzyme broth is sent to the hydrolyzers.

Hydrolysis proceeds by suspending the steam exploded wood in the enzyme-rich broth. The mechanism of hydrolysis is as described earlier. The yields used for the analysis in this study are:

- 88% conversion of the hexosan present in the hemicellulose to hexose sugars;

- 75% conversion of the cellulose to glucose.

The resulting sugar solution is at a relatively high concentration, typically 8.3% by weight such that a sugar concentration step is not required.

The subsequent steps of fermentation and distillation are much the same as those described earlier for acid hydrolysis.

It can be seen that the enzymatic hydrolysis process is a potentially attractive means of wood saccharification due to its improved yields of sugars over acid hydrolysis. Because of the specificity of the enzymes and, consequently, the lack of polysaccharide degradation, the yields could, in theory, reach 100%. Furthermore, the process proceeds at low temperature, again reducing degradation of sugars and keeping energy consumption low. There is no need for expensive acid-resistant equipment. Finally, the ligneous residues remain in a reactive form, suitable for further chemical conversion.

The main disadvantage of the process is its lack of commercial experience, although there has been extensive testing at a laboratory scale. The rates of hydrolysis are slow compared to acid hydrolysis and the performance is sensitive to the wood feedstock.

3. Process Design

The process design for the enzymatic hydrolysis plant was based on a plant design by A.D. Little Inc. for the New York State Energy Research and Development Authority (1985). The overall block flow diagram is shown in Figure IV-7.

(a) Feedstock Handling and Storage

The feedstock handling system for the enzymatic hydrolysis plant is basically the same as that for the acid hydrolysis plant. The capacities of the plants were 10, 25 and 50 million litres of ethanol product per year. Feedstock is purchased for the two larger plants and obtained completely from a nearby sawmill for the smallest plant.

(b) Steam Explosion Pretreatment

The steam explosion reactor is charged with a batch of wood, closed, and saturated steam at 600 psig is introduced and allowed to permeate the wood. During the cooking period, some cellulose-lignin bonding is destroyed, and hemicelluloses are hydrolyzed to pentoses and hexoses. To minimize the degradation of these sugars, steaming time must be kept

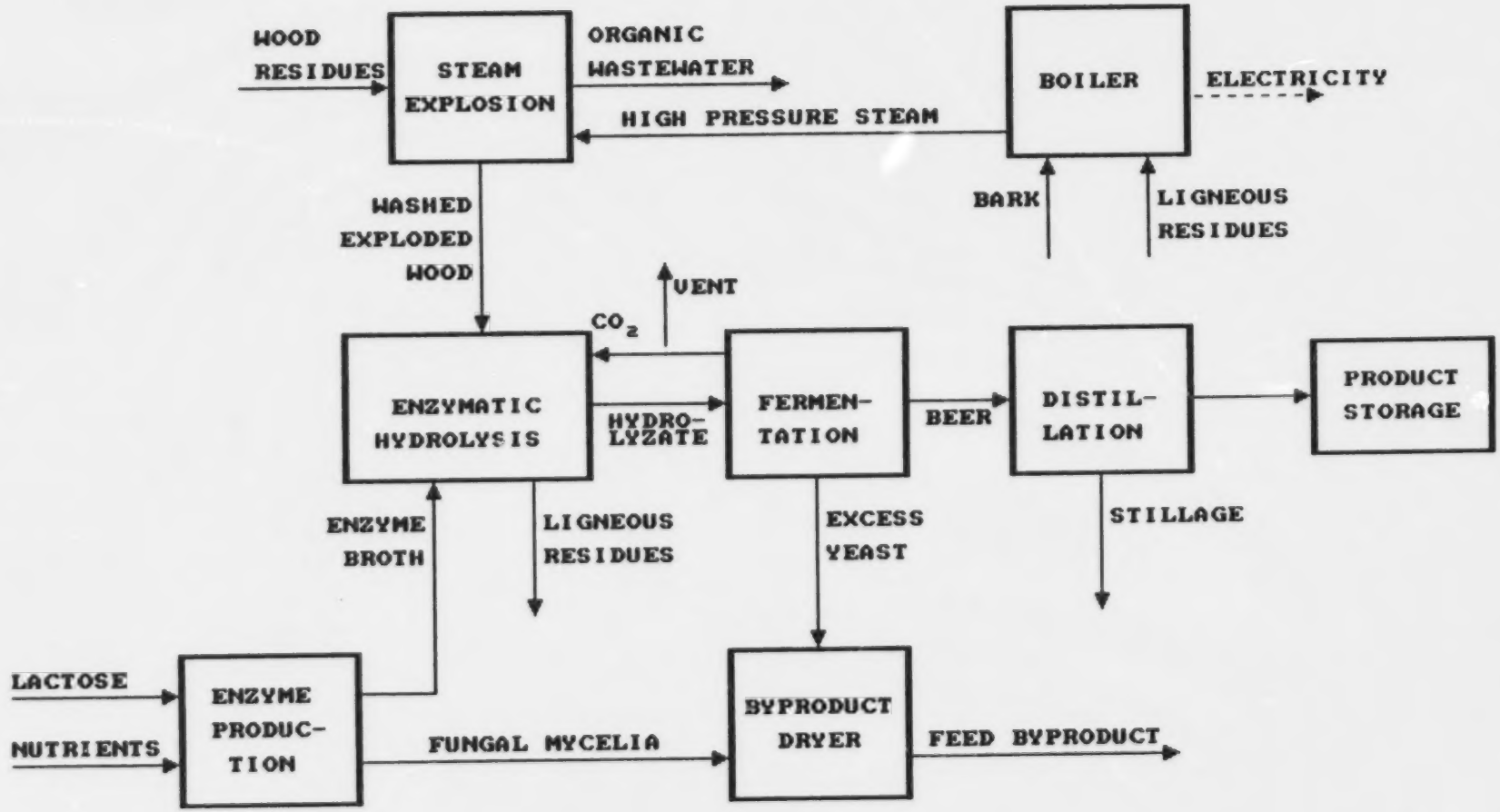

FIGURE IV-7 SIMPLIFIED PROCESS DIAGRAM FOR AN ENZYMATIC HYDROLYSIS PLANT

short, but not so short that delignification and collapse of the crystalline structure cannot occur. Typical residence times are 30 seconds to 2 minutes. After cooking, the wood charge is suddenly released to lower pressure, effectively destroying the wood matrix, liberating the wood fibres and increasing the surface area of the cellulose. The steam requirements are modelled as 2.0 kg steam/kg of dry wood input. The discharged steam is used to heat boiler feedwater, producing low pressure steam at the rate of 0.7 kg L-P steam/kg H-P steam.

It was assumed that only hemicellulose was degraded by steam explosion with 25% of the input pentosans being lost.

The steam exploded fibres are sent to the hydrolysis section.

(c) Enzyme Production

The enzyme production section is based on the work of Allen and Andreotti (1982) and Ryu et al (1979), as described by Little, 1985. The proposed carbon source is lactose from cheese whey permeate. Whey is the leftover fluid when milk is curdled to produce cheese. In recent years, cheese producers have been recovering the protein left in the whey, leaving a lactose-rich whey permeate. Whey permeate, containing 15% to 16% lactose, is trucked to the ethanol plant and stored.

Cellulase enzymes are produced in continuous, aerobic fermentors by *Trichoderma reesei*, which is cellulase hyper-producing. Seed inoculum is supplied for the initial start-up and enzyme production proceeds with the addition of the carbon source (lactose) and nutrients. The fermented beer is continuously removed and suspended solids are settled out. These solids are washed to recover any additional enzyme, and dewatered for by-product use, which will be explained later. The

enzyme broth is sent to the hydrolyzer, and the ratio of enzyme to wood substrate is 20 IU/gram[2].

(d) Hydrolysis

The hydrolysis tanks are charged with the enzyme broth, and steam-exploded wood is added in fed batch mode over a 24 hour period. The pH of the hydrolysis slurry is controlled at 4.8 with the addition of ammonia, while the temperature is controlled at 48°C through the use of low pressure steam. The hydrolysis process is maintained under anaerobic conditions by sparging CO_2 into the reactor. The ratio of enzyme to substrate is 20 IU/gram. The total hydrolysis time is 72 hours, after which the hydrolysis vessels are drained and cleaned in place.

The resulting hydrolyzate is pumped to centrifuges, and separated into a solids slurry and a clarified hydrolyzate. The slurry is then dewatered to about 50% solids, and the resulting lignin-rich filter cake is used as a by-product. The filtrate and centrate are combined, giving a hydrolyzate containing about 9.3% total sugars (hexose and pentose) by weight which is sent to fermentation.

(e) Fermentation and Distillation

The fermentation and distillation sections are similar to those described earlier for the acid hydrolysis plant and so will not be discussed further here.

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[2] An IU, or International Filter Paper Unit, is defined in terms of the amount of sugar produced per unit time from a strip of Whatman filter paper (Wright, 1988).

(f) By-product Processing

The main component of the by-product processing area is a steam tube dryer, which is used to mix and dry the excess yeast from fermentation and fungal mycelia from enzyme production. The high protein product contains about 10% moisture content and is saleable as animal feed.

4. Product and By-products

There are a number of products and by-products associated with the enzymatic hydrolysis plant, including ethanol, lignin, animal feed products, pentose sugars, steam and electricity. The main product, ethanol, has been discussed earlier.

By-products from enzymatic hydrolysis differ from those for acid hydrolysis, particularly with respect to the ligneous residues. Because process conditions used for enzymatic hydrolysis are comparatively mild, the lignin has a low molecular weight, a low degree of carbon-carbon cross-linking and a high phenolic content (Foody, 1987). As a result, the lignin is chemically reactive and can be sold as a precursor for lignin chemicals, rather than simply burned as fuel.

One of the principle potential uses for lignin is in the area of phenolic substitution. Lignin could either replace phenol in phenol formaldehyde thermosetting resins (commonly used in composite panelboards), or more conservatively, be used in combination with phenols as a glue extender.

Two animal feed products result from enzyme hydrolysis: pentose molasses and a yeast by-product. The pentose molasses can be sprayed on or mixed with feed to enhance flavour or palatability. The yeast by-product

is a protein-rich, dried blend of the excess yeast from the fermentors and the dewatered fungal mycelia from enzyme production. The principal application of this product would be as a dairy livestock feed.

5. Assessment of the Status of Available Technology

Enzymatic hydrolysis of biomass to fermentable sugars has yet to be proven on a commercial scale. The areas of the plant identified as having the highest degree of uncertainty are the steam explosion, enzyme production and hydrolysis steps. Materials handling and storage, fermentation and distillation are essentially proven processes.

The steam explosion process has been used at the commercial scale, but primarily with hardwood feedstocks. This process has not yet proved useful for softwood species (Wayman, 1986). However, Wayman (1987) reports that "coniferous wood can be made as amenable to enzymatic hydrolysis by steam as is hardwood" by using gaseous SO_2 as a catalyst in prehydrolysis at a ratio of 2.0% to 2.6% of the dry wood weight.

The production of cellulase enzymes has been demonstrated at the laboratory scale, but there are concerns with most biological processes that they will perform differently when scaled-up (Little, 1985). Yeast cultures are susceptible to contamination and reversion, and such process upsets could dramatically affect hydrolysis.

The enzymatic hydrolysis step is one of the areas of greatest uncertainty. Hydrolysis is performed under anaerobic, slightly acidic conditions to prevent infection of the yeast. However, the design calls for aseptic operation for a 72 hour period. There is also a potential problem with localized inactivation of the enzymes by heat where steam is injected to maintain reaction temperatures.

The subsequent fermentation step is readily achieved commercially using conventional sugars, but the fermentability of enzyme-derived hydrolyzates has yet to be proven at full scale.

The lignin by-product, which is chemically reactive in theory, has yet to be demonstrated as a marketable alternative to phenolic resins.

Current research activities in enzymatic hydrolysis include:

- fermentation of xylose and other 5-carbon sugars using unconventional yeasts such as *Pichia-stipitis* (Wayman, 1986), which are reported to have higher ethanol tolerances than *Saccharomyces cerevisiae*;

- simultaneous saccharification and fermentation (SSF), that is hydrolysis and fermentation in the same reaction vessel. This method helps to overcome end-product inhibition by fermenting the glucose to ethanol as soon as it is formed (Wright, 1988);

- SO_2 catalyzed prehydrolysis (Wayman, 1986) to render softwoods more amenable to steam explosion;

- organosolv pretreatment (Wright, 1988) which uses an organic solvent (ethanol or methanol) to separate the feedstock into a solid cellulose residue, a solid lignin which is essentially reactive, and a liquid stream containing the pentosan sugars.

V. CASE STUDIES OF ETHANOL PLANT/SAWMILL COMBINATIONS

A. Methodology

Case studies were done for ethanol plants which could be supplied with a sufficient amount of sawdust and shavings by either a single sawmill or a small localized group of sawmills. The sawmills considered for analysis were those typical of the interior of British Columbia. These mills typically range in size from 25 MMfbm/yr to 250 MMfbm/yr (59,000 to 590,000 m^3/yr), with many having a nominal annual production of 50 to 150 MMfbm/yr (118,000 to 354,000 m^3/yr). The same ethanol plant sizes were used for both acid and enzymatic hydrolysis based plants, in spite of the difference in ethanol yields which exist for the processes, so that the costs of the plants could be compared on an equitable basis.

Material and energy balances and estimates of capital and operating costs were developed for all of the ethanol plants considered in this study, using a computer simulation program called BIOSIM, which was developed for analysis of bioenergy systems. A description of the design and capabilities of BIOSIM has been given in a paper by Edwards and Wasik (1989) and in a report by H.A. Simons Ltd. and B.H. Levelton & Associates (1988). The version of BIOSIM available at the start of this project included the unit processes for bioenergy systems shown in Figure V-1. To these were added the following unit process simulation modules:

- enzymatic hydrolysis, which includes: steam explosion; enzymatic hydrolysis; and enzyme production;

- continuous fermentation (batch fermentation was included in the original BIOSIM);

- yeast mycelia steam dryer.

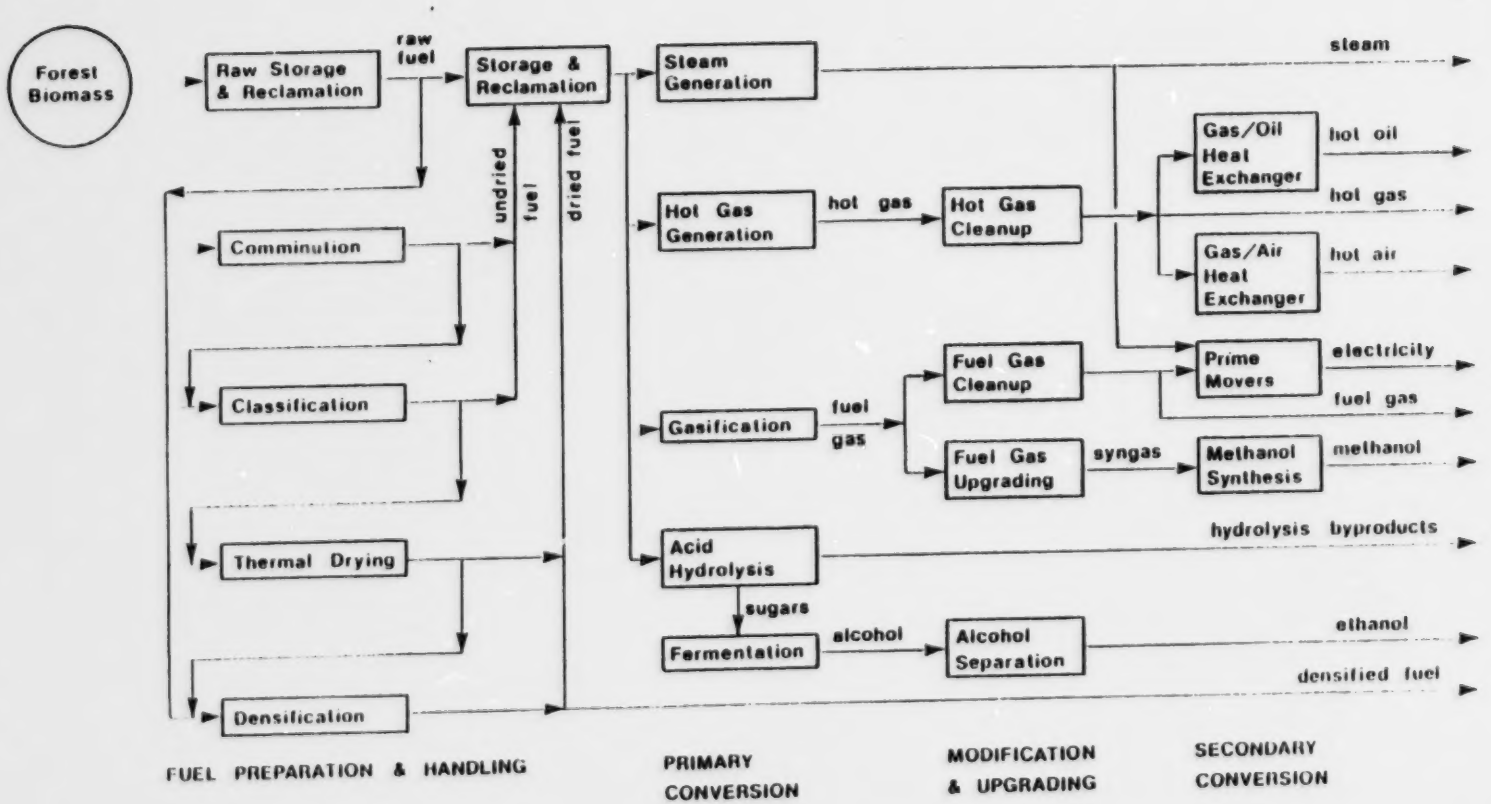

FIGURE V-1 UNIT PROCESSES AND SYSTEMS INCLUDED IN BIOSIM

The additional modules were merged with the existing library simulation modules so that they are an integral part of the BIOSIM program package.

The simulation modules previously included in BIOSIM were developed from technical and cost data compiled from various sources in ENFOR Project C-258 (Levelton and Elliott, 1983). The modules simulate steady-state operation and incorporate correlations for material conversions, energy requirements, consumption of chemicals steam, electricity and water and capital and maintenance costs. The modules do not estimate labour costs for the plant or office. The modules added to BIOSIM in this study were developed to be consistent in form and content with existing modules.

Capital costs estimated by BIOSIM apply to a previous reference year. These were brought forward to 1988 using published indexes. Costs of consumables were estimated using 1988 unit prices and therefore did not need to be scaled. Labour costs were estimated separately using 1988 labour rates for operating personnel.

BIOSIM allows the user to select unit processes and to specify user-specific values or accept default values for all parameters needed to describe the plant being analyzed. The user makes selections and inputs data using a series of menus which are coordinated by the main BIOSIM program and provide explanatory material to assist the user. Various verification tests are made by BIOSIM to check for obvious data entry errors and for incompatibilities in process selections and input data. User instructions and example simulations are provided in the report by Simons and Levelton (1988).

B. Case Studies Analyzed

As shown in Chapter II for sawmills having sizes typical of the interior of British Columbia, sawdust and shavings are produced in amounts ranging from 24,800 ODt/yr for a 50 MMfbm/yr mill to 74,800 ODt/yr for a 150 MMfbm/yr mill.

For the smaller mill, this waste could be converted to about 6 ML/yr using acid hydrolysis and about 7 ML/yr using enzymatic hydrolysis. For the larger mill, 18 to 21 ML/yr could be produced with acid hydrolysis and enzymatic hydrolysis, respectively. Larger ethanol plants could be supported by combining the waste streams from a group of mills in a local area.

Based on the quantities of sawdust and shavings available at sawmills in the interior of B.C., three sizes were chosen for analysis: 10, 25 and 50 ML/yr. The smallest plant would be appropriate for coupling to a single mill of 100 MMfbm/yr, or a smaller mill with some purchase of wastes from external sources. A 50 ML/yr plant could be operated with sawdust and shavings from two or more mills with an aggregate production of some 400 MMfbm/yr. A 25 ML/yr plant was examined to illustrate more clearly the effect of plant size on the economics of producing ethanol from wood waste.

The feedstock used for all the case studies was balsam fir. This species was chosen because fairly complete composition data are available and it is representative of true firs and other softwoods present in the study area. Sawmills in the study area process a mixture of fir, pine and spruce. Table V-1 summarizes the composition data for balsam fir relevant to the analysis of conversion to ethanol.

The type of residue used in the ethanol plant was planer shavings and sawdust. These residues were assumed to be available on site for the 10 ML/yr plant, and purchased outside the plant gate for the 25 and 50 ML/yr plants. The moisture content of the sawdust and shavings was taken to be 45%, wet basis.

The final product from the ethanol plants is anhydrous ethanol, a mixture of 99.5% by weight of ethanol in water. BIOSIM can also simulate production of

TABLE V-1 CHEMICAL COMPOSITION OF BALSAM FIR FEEDSTOCK USED FOR PROCESS DESIGN

COMPONENTS	WT%, DRY BASIS	WT%, EXTRACTIVE-FREE BASIS
Ash	0.19	0.20
Lignin	28.50	29.40
Carbohydrate	63.55	65.50
Hexosans		
Mannan	12.03	12.40
Galactan	0.97	1.00
Glucan	45.40	46.80
	58.40	60.20
Pentosans		
Araban	0.49	0.50
Xylan	4.66	4.80
	5.15	5.3
Other	4.76	4.9
Extractives	3.00	---
	100	100

GROSS COMPOSITION	WT%, DRY, EXTRACTIVE-FREE ASH-FREE BASIS
Cellulose	44.0
Hemicellulose	27.0
Lignin	29.0
	100.0

Source: Mullins and McKnight, 1981

hydrous ethanol (95% by wt), but for this study, only anhydrous ethanol was considered.

Unit process selections and sizing data used to develop the BIOSIM simulation for an acid hydrolysis based ethanol plant producing 25 ML/yr are summarized in Appendix A for reference. Comparable input data was used to develop the simulations for the other sizes and types of plants considered in this study. The selections and sizing data used for the plants is considered representative of what would be used in a commercial ethanol plant.

C. Acid Hydrolysis Based Ethanol Plants

Simulations of acid hydrolysis based plants were developed for nominal rated capacities of 10, 25 and 50 ML/yr when operating at 100% load and 350 days per year. Figure V-2 illustrates the mass flow rates of major process streams for a plant producing 25 ML/yr. The flow rates for larger and smaller plants may be estimated from the ones shown by scaling linearly.

The primary product of the plant is ethanol, while the primary by-products are fodder yeast, furfural and pentose concentrate. Carbon dioxide, a fermentation by-product, is vented to atmosphere.

Table V-2 summarizes the capital costs of the ethanol plants studied, itemized by plant section. The largest cost centre is "offsites", which includes:

- steam generation (fueled using lignin residue);
- electricity generation;
- water treatment;
- cooling tower;
- storage and shipping;

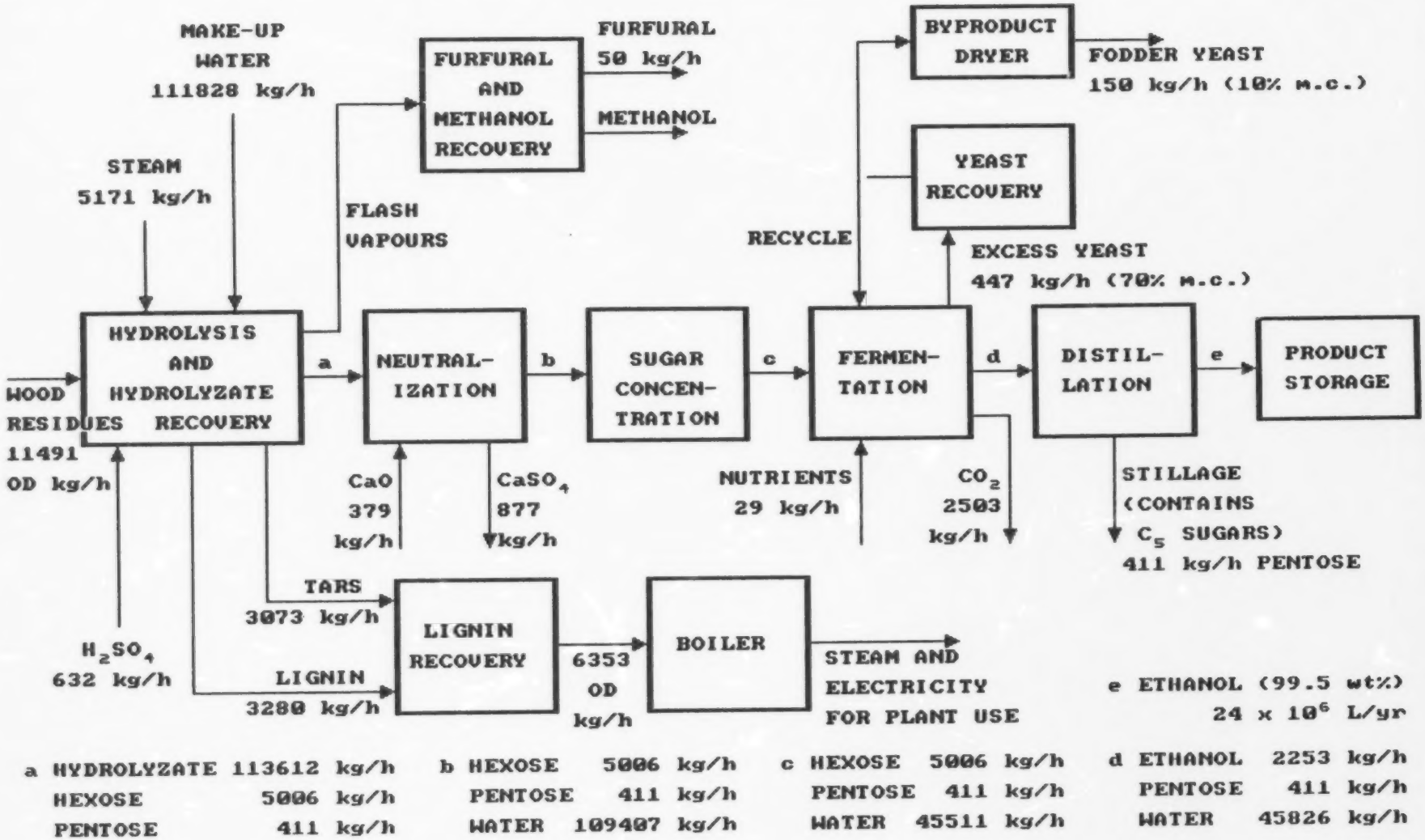

FIGURE V-2 BLOCK DIAGRAM OF A 25 ML/yr ACID HYDROLYSIS ETHANOL PLANT SHOWING MASS FLOW RATES

TABLE V-2 CAPITAL COSTS FOR ACID HYDROLYSIS PLANT

PLANT SECTION	ETHANOL PLANT CAPACITY (ML/yr) 10	25	50
Hydrolysis			
Hydrolyzer	$ 2,556,100	$ 4,642,400	$ 7,284,600
Neutralizer	357,500	679,800	1,104,400
Concentrator	343,900	596,500	904,100
Furfural Recovery	530,800	920,800	1,395,700
Subtotal	3,778,300	6,839,500	10,688,800
Fermentor	1,224,900	2,124,800	3,220,500
Product Dryer	169,000	293,100	444,200
Distillation	1,441,300	2,500,300	3,789,700
Offsites	11,057,900	19,187,400	29,074,900
Materials Handling & Storage	709,900	1,197,700	1,697,400
Subtotal	18.39×10^6	32.14×10^6	48.91×10^6
Contingency (15%)	2.76×10^6	4.82×10^6	7.34×10^6
Total	$ 21.15×10^6	$ 36.96×10^6	$ 56.25×10^6

- fire protection;
- distribution of steam, water and electricity;
- buildings;
- general site preparation.

A 15% contingency on capital costs has been included.

By world standards, the plants considered here are small and, consequently, relatively expensive per annual litre. Capital costs decrease from $ 2.20/annual L for the smallest plant to $ 1.17/annual L for the largest plant.

Operating costs are summarized in Table V-3. The cost of feedstock used for the base case is $ 10/ODt, which was provided by industry and is typical of the transportation cost of mill residues over short distances. The cost of utilities and chemicals is based on 1988 unit prices for western Canada quoted by suppliers. Electricity consumption covers only supplemental electricity. The plant cogenerates sufficient electricity for its own use along with process steam. Maintenance costs were taken to be 5% of the total capital cost. The estimate of operating labour cost was developed assuming 24 h/d operation and using an average salary, with fringes and benefits, of $ 50,000/yr. An allowance of 15% on operating labour cost was used for direct supervisory and office staff.

The plant produces 9.6, 24 and 48 ML/yr with a yield of 240 L/ODt (Table V-3). Of the saleable by-products, pentose concentrate is the largest, followed by furfural and fodder yeast.

Operating costs decrease from $ 0.35/annual L for the smallest plant to $ 0.20/annual L for the largest plant.

TABLE V-3 ACID HYDROLYSIS PLANT - SUMMARY OF MATERIAL FLOWS AND OPERATING COSTS

		ETHANOL PLANT CAPACITY (ML/yr)		
		10	25	50
Feedstock				
Biomass	(ODt/yr)	40,080	100,390	200,770
	($)	400,840	1,003,850	2,007,700
Consumption				
Electricity	(KWh/yr)	659,600	1,023,800	1,176,900
	($)	26,380	40,950	47,070
Transportation Fuel	(L/yr)	28,450	36,820	52,390
	($)	14,220	18,410	26,190
Water	(KL/yr)	522,800	1,309,400	2,618,800
	($)	0	0	0
Diammonium Phosphate	(t/yr)	21	53	106
	($)	9,910	24,810	49,630
Urea	(t/yr)	78	194	388
	($)	26,360	66,010	132,030
Sulphuric Acid	(t/yr)	2,120	5,310	10,620
	($)	317,970	796,320	1,592,650
Lime	(t/yr)	1,272	3,185	6,371
	($)	127,190	318,530	637,060
Maintenance	($)	1.0575×10^6	1.848×10^6	2.8125×10^6
Manpower	($)	1.4×10^6	1.8×10^6	2.3×10^6
Total Operating Costs	($)	3.380×10^6	5.917×10^6	9.605×10^6

TABLE V-3 ACID HYDROLYSIS PLANT - SUMMARY OF MATERIAL FLOWS AND OPERATING COSTS (CONTINUED)

		ETHANOL PLANT CAPACITY (ML/yr)		
		10	25	50
Production				
Ethanol	(10^6 L/yr)	9.6	24.0	48.0
CO_2	(t/yr)	8,400	21,030	42,050
Yeast	(t/yr)	504	1,260	2,520
Pentose	(t/yr)	1,378	3,450	6,900
Furfural	(t/yr)	527	1,319	2,640

D. Enzymatic Hydrolysis Based Ethanol Plants

As for the acid hydrolysis cases, simulations were developed for 10, 25 and 50 ML/yr plants. Figure V-3 illustrates the mass flow rates of major process streams for a plant having a rated nominal capacity of 25 ML/yr. Enzymatic hydrolysis based ethanol plants produce fodder yeast, pentose concentrate and lignin as saleable by-products. The lignin is left in a reactive form after processing and is suitable for subsequent conversion to other chemical products. As with acid hydrolysis based ethanol plants, CO_2 is vented to atmosphere from the fermentation section.

The capital costs for the three plant sizes are given in Table V-4. Offsites are a large proportion of the total capital costs, including:

- steam generation (fueled using wood waste);
- electricity generation;
- water treatment;
- cooling tower;
- storage and shipping;
- fire protection;
- distribution of steam, water and electricity;
- buildings;
- general site preparation.

A contingency allowance of 15% on capital costs has been included.

Capital costs of the enzymatic hydrolysis based ethanol plants are higher than those based on acid hydrolysis. The capital costs decrease from $ 3.21/annual L for the smallest plant to $ 1.69/annual L for the largest plant. The higher costs are attributable to the steam explosion and enzyme production

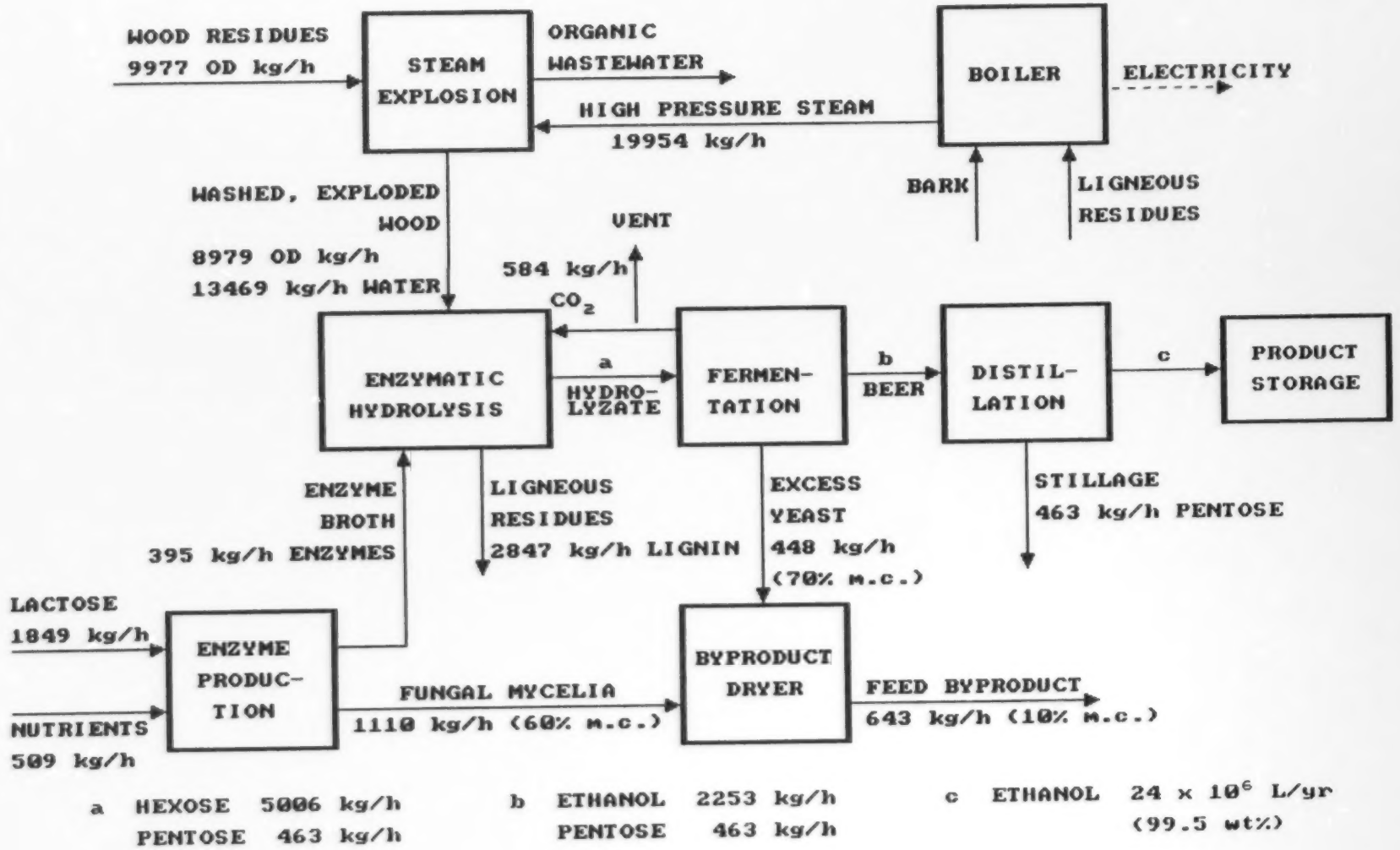

FIGURE V-3 BLOCK DIAGRAM OF A 25 ML/yr ENZYMATIC HYDROLYSIS ETHANOL PLANT SHOWING MASS FLOW RATES

TABLE V-4 CAPITAL COSTS FOR ENZYMATIC HYDROLYSIS PLANT

PLANT SECTION	ETHANOL PLANT CAPACITY (ML/yr) 10	25	50
Hydrolysis			
Steam Explosion	$ 1,504,500	$ 2,609,700	$ 3,955,600
Hydrolyzer	4,688,100	8,132,500	12,328,300
Enzyme Production	5,770,500	10,010,000	15,175,900
Subtotal	11,963,100	20,752,200	31,459,800
Fermentor	1,382,500	2,398,300	3,635,100
By-product Dryer	331,200	574,600	870,900
Distillation	1,441,300	2,500,300	3,789,700
Offsites	11,057,900	19,187,400	29,074,900
Materials Handling & Storage	642,800	1,141,800	1,583,200
Subtotal	26.82×10^6	46.55×10^6	70.41×10^6
Contingency (15%)	4.02×10^6	6.98×10^6	10.56×10^6
Total	30.84×10^6	53.53×10^6	80.97×10^6

sections of the plant. The hydrolysis section, in total, amounts to 24% of the total capital cost.

Operating costs for the plants are summarized in Table V-5. These include the costs of feedstock, enzyme production nutrients, lactose as an enzyme carbon source, maintenance, labour and various other consumables.

The cost of wood feedstock was set at $ 10/ODt as per data provided by industry. The unit prices for electricity, transportation fuel and various consumable chemicals were based on 1988 prices provided by suppliers.

A significant cost component for the enzymatic hydrolysis plant is the cost of the substrate for enzyme production. Cheese whey was selected as the substrate because of its availability and the present lack of a suitable means of disposal. The cost of cheese whey was obtained from Dairyland Foods (Giles, 1989), which operates cheese plants in the interior of B.C. and in the Greater Vancouver area. Cheese whey is presently a disposal problem and could be obtained at present for the cost of shipping only. However, various uses of the whey are being considered, making its availability and price in the medium term uncertain. For the analysis in this study, cheese whey is assumed to be available for the cost of shipping.

The overall ethanol yield obtained for the enzymatic hydrolysis plants was about 286 L of ethanol per oven-dried tonne of wood feedstock. This figure, while higher than that obtained for acid hydrolysis, can be considered a conservative estimate. The conversion of cellulose to glucose was modelled at 75%, though yields cited in the literature (Wayman, 1986) have been as high as 90% with use of appropriate hydrolysis conditions.

TABLE V-5 ENZYMATIC HYDROLYSIS PLANT - SUMMARY OF MATERIAL FLOWS AND OPERATING COSTS

		ETHANOL PLANT CAPACITY (ML/yr)		
		10	25	50
Feedstock				
Biomass	(ODt/yr)	33,460	83,800	167,610
	($)	334,640	838,070	1,676,150
Consumption				
Electricity	(KWh/yr)	471,400	1,021,700	1,170,900
	($)	18,860	40,870	46,840
Transportation Fuel	(L/yr)	27,770	34,900	48,160
	($)	13,880	17,450	24,080
Water	(KL/yr)	522,850	1,309,410	2,618,800
	($)	0	0	0
Diammonium Phosphate	(t/yr)	21	53	106
	($)	9,910	24,810	49,630
Urea	(t/yr)	78	194	388
	($)	26,360	66,010	132,030
Lactose	(t/yr)	6,203	15,535	31,071
	($)	992,480	2,485,600	4,971,360
Nutrients	(t/yr)	1,708	4,277	8,553
	($)	683,040	1,710,640	3,421,280
Maintenance	($)	1.542×10^6	2.6765×10^6	4.0485×10^6
Manpower	($)	1.6×10^6	2×10^6	2.75×10^6
Total Operating Costs	($)	5.221×10^6	9.860×10^6	17.120×10^6

TABLE V-5 ENZYMATIC HYDROLYSIS PLANT - SUMMARY OF MATERIAL FLOWS AND OPERATING COSTS (CONTINUED)

		ETHANOL PLANT CAPACITY (ML/yr)		
		10	25	50
Production				
Ethanol	(10^6 L/yr)	9.6	24.0	48.0
CO_2	(t/yr)	8,400	21,030	42,050
Yeast	(t/yr)	2,158	5,405	10,809
Pentose	(t/yr)	1,552	3,887	7,774
Lignin	(t/yr)	9,557	23,919	47,837

VI. ECONOMIC ANALYSIS

Economic analyses were conducted for each plant type and size, in order to determine return on investment. Sensitivity analyses were used to determine the effect of varying such economic parameters as product and by-product selling prices, feedstock prices and total capital costs on plant profitability.

A. Methodology for Economic Analysis

Economic analyses were conducted using a Lotus 1-2-3 spreadsheet template known as RETA 123 (Renewable Energy Technology Applications). This program was provided by Mr. Jay C. Barclay, Energy, Mines and Resources, Canada. RETA 123 accepts inputs on capital and operating costs, economic parameters and key plant operating data. Economic analysis methodologies are included and can be used to report:

- present value of capital costs, expenses and revenue;
- net present value;
- profit index;
- internal rate of return;
- payback period.

A complete RETA 123 input/output listing is given in Appendix B for reference.

Table VI-1 lists the cost and performance input data specified and the values for the economic parameters common to all analyses.

Although a number of profitability indicators are generated by RETA 123, the one used in this study was the internal rate of return (ROI). The results of the

TABLE VI-1 SPECIFIED AND CONSTANT INPUTS FOR THE RETA 123 ECONOMIC MODEL

Labels	
Project Code	Technology
Description	Application/Sector
Project Name	Location
Energy Source	Investor
Constant Parameters	
Annual inflation rate	5%
Marginal income tax rate	45%
Real cost of capital	10%
Real social cost of capital	5%
Base year	1988
Discount year	1988
In-service year	1989
Lifetime	20
Capital	
Investment cost capital expenditures	
- year 1	50%
- year 0	50%
Depreciation	
Year 1	25%
Year 2	50%
Year 3	25%
Expenses	
Feedstock	
- annual quantity	
- price	
- escalation (real)	
Operating and Maintenance Costs	
- escalation (real)	0%

TABLE VI-1 SPECIFIED AND CONSTANT INPUTS FOR THE RETA 123 ECONOMIC MODEL (CONTINUED)

Revenues	
Ethanol	
- annual production	
- price	
- escalation (real)	0%
By-product 1	
- annual production	
- price	
- escalation (real)	0%
By-product 2	
- annual production	
- price	
- escalation (real)	0%
Incentives:	None

analyses were compared to a "hurdle" ROI of 20%, a value indicated by a number of the sawmill companies to be the minimum which would be considered for an ethanol plant.

B. Prices of Plant Products and Feedstocks

The economics of the acid and enzymatic hydrolysis based ethanol plants were determined for a set of base conditions.

To calculate return on investment for the ethanol plants it is necessary to specify the expected revenues from the sale of ethanol and plant by-products. Values for these materials were developed with input from suppliers of comparable commodities. These prices are somewhat uncertain because a proven market does not presently exist in the study area for many of the products of the plant. Product price would be dependent on quality and, to develop a market share, would probably need to be less than alternate products. The prices of plant products and feedstocks used for base case analyses are summarized in Table VI-2.

The price of ethanol was developed from discussions with Mohawk Oil (O'Connor, 1988) and allowed for the octane and fuel value of ethanol when mixed to a 10% concentration in gasoline. The price is derived as follows:

Octane Value:	$ 0.03/L x 1/0.1	= $ 0.30/L
Fuel Value:		= $ 0.20/L
		$ 0.50/L ethanol

The assumed price of lignin from the enzymatic hydrolysis plant was based on a review of comparable chemicals by Nystrom et al (1985). Unmodified lignosulfonates were priced at $ 0.04 - $ 0.05 per pound (95% solids basis) in the

TABLE VI-2 PRICES OF PLANT PRODUCTS AND FEEDSTOCKS

MATERIAL	PRICE
Products	
Ethanol	$ 0.50/L
Fodder yeast	$ 300/tonne
Pentose sugar	$ 100/tonne
Furfural	$ 1000/tonne
Lignin (enzymatic hydrolysis)	$ 150/tonne
Feedstocks	
Wood	$ 10/OD tonne
Cheese whey/lactose	$ 160/tonne lactose

United States in 1984. Specialty grades ranged from $ 0.07 to $ 0.40 per pound. This product suggests a low-end price for lignin from the plant of about $ 150/tonne, after allowance for inflation and exchange rates. Foody (1987) did a review of lignin markets and prices, finding that prices could vary from $ 250/tonne based on urea replacement in resins to $ 560/tonne as a phenol replacement. The target lignin price was determined by Foody (1987) to be about one-half of the price of phenol, which would be about $ 750/tonne based on the 1989 phenol price in western Canada (Chatterton, 1989). For the base case analysis the lower price of $ 150/tonne suggested in the literature was used.

The price of fodder yeast was assumed equal to the price of canola meal, which has a comparable protein content (35% - 38% protein). The price of canola meal fluctuates $\pm$ $ 100/tonne with the price of soybean meal, but is currently near $ 300/tonne (Pringle, 1989).

The current price for pentose molasses is $ 430/tonne in western Canada (B.C. Sugar, 1989). Nystrom et al (1985) suggested a price for pentose molasses having a 25% moisture content of U.S. $ 75 - $ 94/tonne in 1984, which is equivalent to $ 89 - $ 111/tonne in current Canadian dollars. Foody (1987) used a value of $ 121/tonne. Considering this range of costs and the uncertainty in the market and its quality, a nominal price of $ 100/tonne was used in this study.

Lambert (1989) reviewed the market prices for furfural in the United States. The price in 1988 was U.S. $ 0.75/lb, but in times of abundant supply the price has fallen to U.S. $ 0.40 - $ 0.50/lb. The prices under conditions of abundant supply are currently equivalent to CAN $ 1.00 - $ 1.20/kg. This range is felt to be a realistic expectation for a new furfural source so a value of $ 1.00/kg was used for the base case analysis.

Cheese whey is the feedstock for enzyme production. Its cost was calculated as the cost of transportation only, with 75% being supplied from a cheese plant in Abbotsford and the balance from a cheese plant in Armstrong.

C. Base Case Economic Analysis

The results of the economic analyses of acid hydrolysis and enzymatic hydrolysis based ethanol plants are summarized in Tables VI-3 and VI-4. The return on investment for acid hydrolysis based plants increases from a very unattractive level of 9.5% for the 10 ML/yr plant to a reasonably attractive 26.9% for the 50 ML/yr plant. This result is based on a $ 0.50/L selling price for ethanol and prices for by-products as discussed previously. The return on investment for enzymatic hydrolysis plants is somewhat poorer, increasing from 4% for a 10 ML/yr plant to 20.4% for a 50 ML/yr plant. The lower ROI for the enzymatic hydrolysis plants is a consequence of higher capital and operating costs. The magnitudes of the costs for the two processes may be readily compared on a dollar per annual litre basis.

Figure VI-2 illustrates the trend in return on investment with increasing plant size. With the product price assumptions made for the base case analysis, acid hydrolysis clearly has a higher return. The effects of input assumptions on return on investment are investigated in the following section. The economic results indicate that to be attractive to industry, which typically requires an ROI of greater than 20%, an acid hydrolysis based plant should produce over 25 ML/yr. Similarly, an enzymatic hydrolysis plant should produce 50 ML/yr or more.

TABLE VI-3 COSTS, REVENUES AND ECONOMIC INDICATORS FOR AN ACID HYDROLYSIS BASED ETHANOL PLANT

Ethanol Produced (ML/yr)	9.6		24		48	
	($)	($/L)[a]	($)	($/L)	($)	($/L)
Capital Cost	21,150,000	2.20	36,960,000	1.54	56,250,000	1.17
Annual Costs:						
Raw Materials						
- Feedstock	400,840	0.04	1,003,850	0.04	2,007,700	0.04
- Acid	317,970	0.03	796,320	0.03	1,592,650	0.03
- Lime	127,190	0.01	318,530	0.01	637,060	0.01
- Chemicals	36,270	0.004	90,820	0.004	181,660	0.004
Utilities & Miscellaneous	40,600	0.004	59,360	0.002	73,260	0.002
Labour	1,400,000	0.15	1,800,000	0.08	2,300,000	0.05
Maintenance	1,057,500	0.11	1,848,000	0.08	2,812,500	0.06
Total	3,380,400	0.35	5,916,900	0.255	9,604,800	0.20
Annual Revenue:						
Ethanol	4,800,000	0.50	12,000,000	0.50	24,000,000	0.50
Furfural	527,000	0.05	1,319,000	0.05	2,640,000	0.06
Pentose	137,800	0.01	345,000	0.01	690,000	0.01
Yeast	151,200	0.02	378,000	0.02	756,000	0.02
Total	5,616,000	0.58	14,042,000	0.58	28,086,000	0.58
Economic Indicators						
Internal Rate of Return	9.5%		19.6%		26.9%	
Simple Payback Period	9.0 yrs		4.5 yrs		3.0 yrs	

[a] Cost or revenue per annual litre

TABLE VI-4 COSTS, REVENUES AND ECONOMIC INDICATORS FOR AN ENZYMATIC HYDROLYSIS BASED ETHANOL PLANT

Ethanol Produced (ML/yr)	9.6		24		48	
	($)	($/L)[a]	($)	($/L)	($)	($/L)
Capital Cost	30,840,000	3.21	53,530,000	2.23	80,970,000	1.69
Annual Costs:						
Raw Materials						
- Feedstock	334,640	0.03	838,070	0.03	1,676,150	0.03
- Whey	992,480	0.10	2,485,600	0.10	4,971,360	0.10
- Nutrients	683,040	0.07	1,710,640	0.07	301,280	0.07
- Chemicals	36,270	0.004	90,820	0.004	181,660	0.004
Utilities & Miscellaneous	32,740	0.003	58,320	0.002	70,920	0.001
Labour	1,600,000	0.17	2,000,000	0.08	2,750,000	0.06
Maintenance	1,542,000	0.16	2,676,500	0.11	4,048,500	0.08
Total	5,221,170	0.54	9,859,950	0.41	17,119,870	0.36
Annual Revenue:						
Ethanol	4,800,000	0.50	12,000,000	0.50	24,000,000	0.50
Lignin	1,432,650	0.15	3,587,850	0.15	7,175,550	0.15
Pentose	155,200	0.02	388,700	0.02	777,400	0.02
Yeast	647,400	0.07	1,621,500	0.07	3,242,700	0.07
Total	7,035,250	0.74	17,598,050	0.74	35,195,650	0.74
Economic Indicators						
Internal Rate of Return	4.0%		14.1%		20.4%	
Simple Payback Period	14 yrs		6 yrs		4 yrs	

[a] Cost or revenue per annual litre

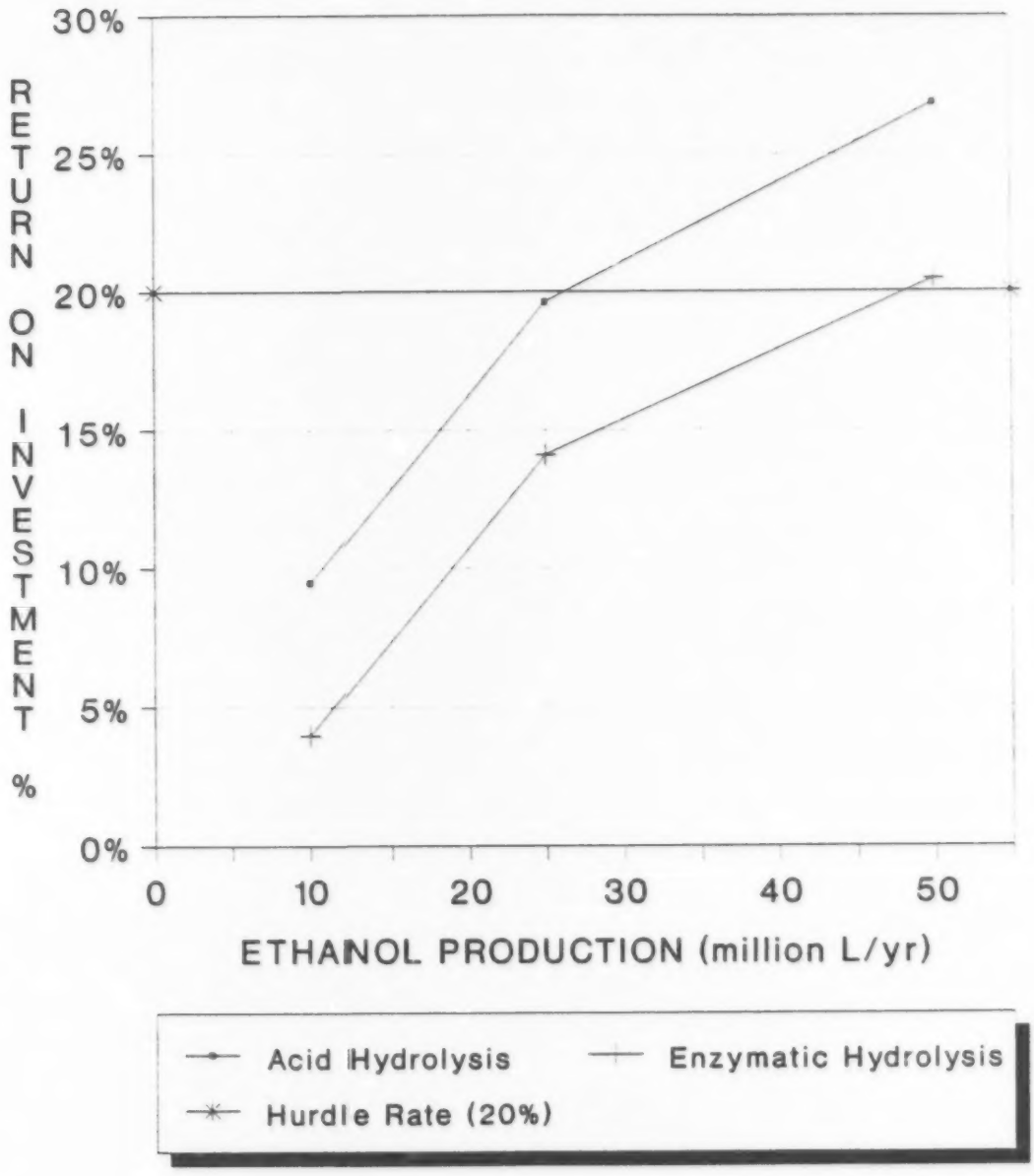

FIGURE VI-1 RETURN ON INVESTMENT FOR ACID AND ENZYMATIC HYDROLYSIS BASED ETHANOL PLANTS

D. Economic Sensitivity Analysis

1. Acid Hydrolysis Based Plants

(a) By-product Credits

In the base case, by-product credits were included in the economic analysis for furfural, pentose and fodder yeast. The by-product prices used are uncertain and may be somewhat conservative. The effect of the by-product credit on return on investment was investigated for the three plant sizes, giving the results shown in Table VI-5. By-product credits used for the base case improve the return on investment about 5% from that for the case of no by-product credits. A similar increase in ROI would occur if the base case by-product credit was doubled.

Increased by-product credits would be possible by:

- production of a high-quality pentose molasses;
- fermentation of pentose to ethanol;
- good market conditions for furfural.

(b) Selling Price of Ethanol

For this sensitivity analysis, the rate of return was determined for a range of ethanol selling prices: $ 0.30/L, $ 0.40/L, $ 0.50/L and $ 0.70/L.

TABLE VI-5 EFFECT OF BY-PRODUCT CREDIT ON ROI FOR AN ACID HYDROLYSIS BASED PLANT

Ethanol production	(ML/yr)	9.6	24	48
ROI for base case	(%)	9.5	19.6	26.9
ROI for no by-product credits	(%)	3.9	14.9	21.8

The base case price, $ 0.50/L, represents the ethanol price in the fuel additive market. The two lower prices represent the price that ethanol from wood may have to sell at to enter the fuel additive market. The high price, $ 0.70/L, represents the chemical grade ethanol price.

The results of this analysis are given in Figure VI-2. At no point does the 10 million L/yr plant achieve a 20% ROI. The 25 million L/yr plant reaches the hurdle rate at a selling price of $ 0.50/L and up, while the 50 million L/yr plant does so for prices of $ 0.40/L and up. The results demonstrate the obvious benefits of economics of scale and suggest a plant of 50 ML/yr is the preferred size where sufficient residues are available.

(c) Feedstock Price

The price of the wood feedstock was varied from $ 10/ODt to $ 80/ODt. The lower figure of $ 10/ODt wood was quoted by sawmill representatives for their excess residues which have no value for pulping. The higher value of $ 80/ODt is approximately the price of pulp chips, as indicated by industry. A medium range price of $ 40/ODt was also used to represent mixtures of excess residues and chips.

Using these three prices, it was possible to determine the ethanol selling price needed to achieve a 20% ROI for each case. The results are shown in Figure VI-3.

The graph is essentially linear, and shows that in order to achieve a 20% ROI using pulp chips, the ethanol would have to be sold for $ 1.09/L. This is well above the current ethanol fuel additive market price of $ 0.50/L, and confirms that the only economically feasible feedstock is

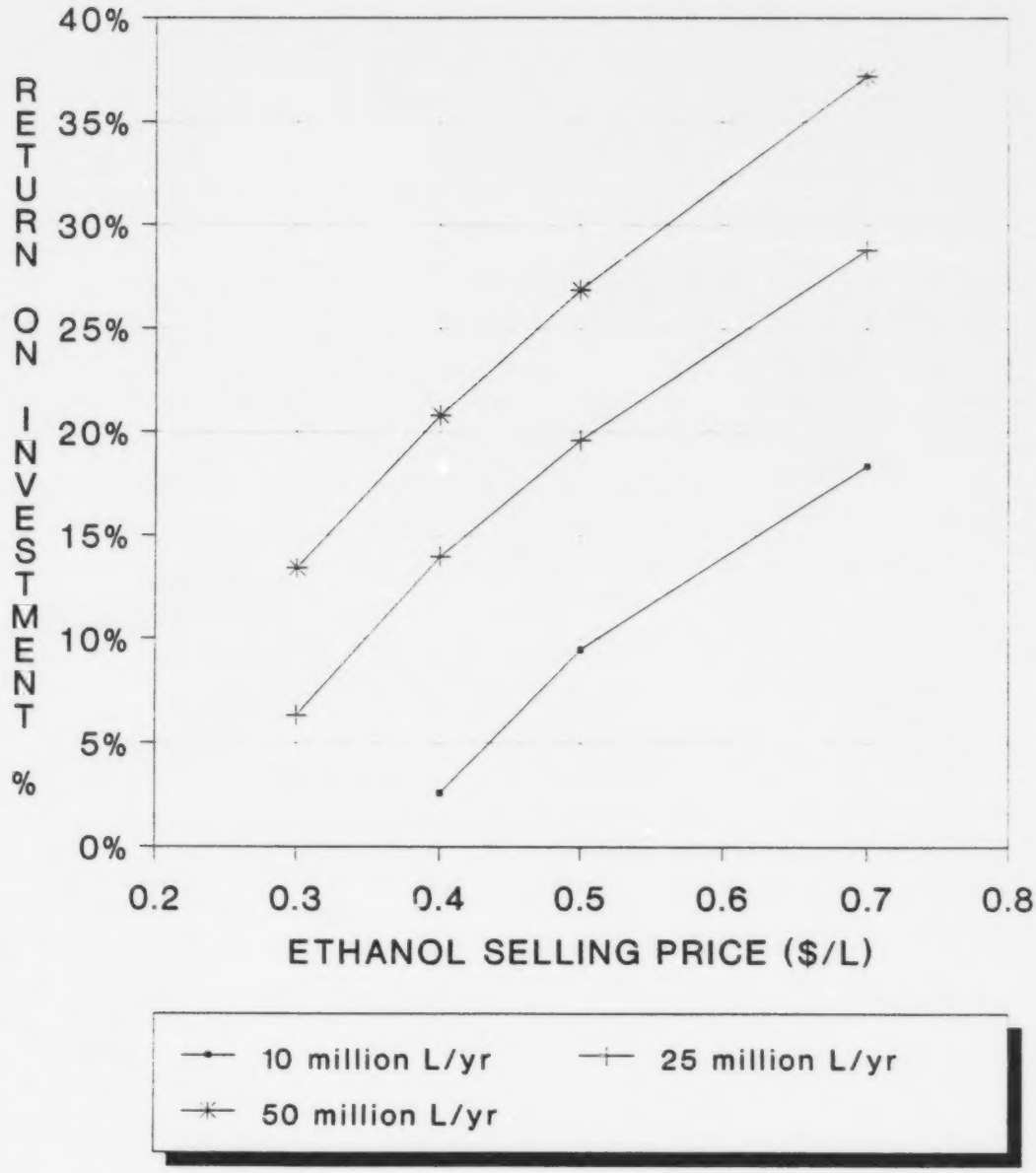

FIGURE VI-2 EFFECT OF ETHANOL SELLING PRICE ON RETURN ON INVESTMENT FOR AN ACID HYDROLYSIS BASED PLANT

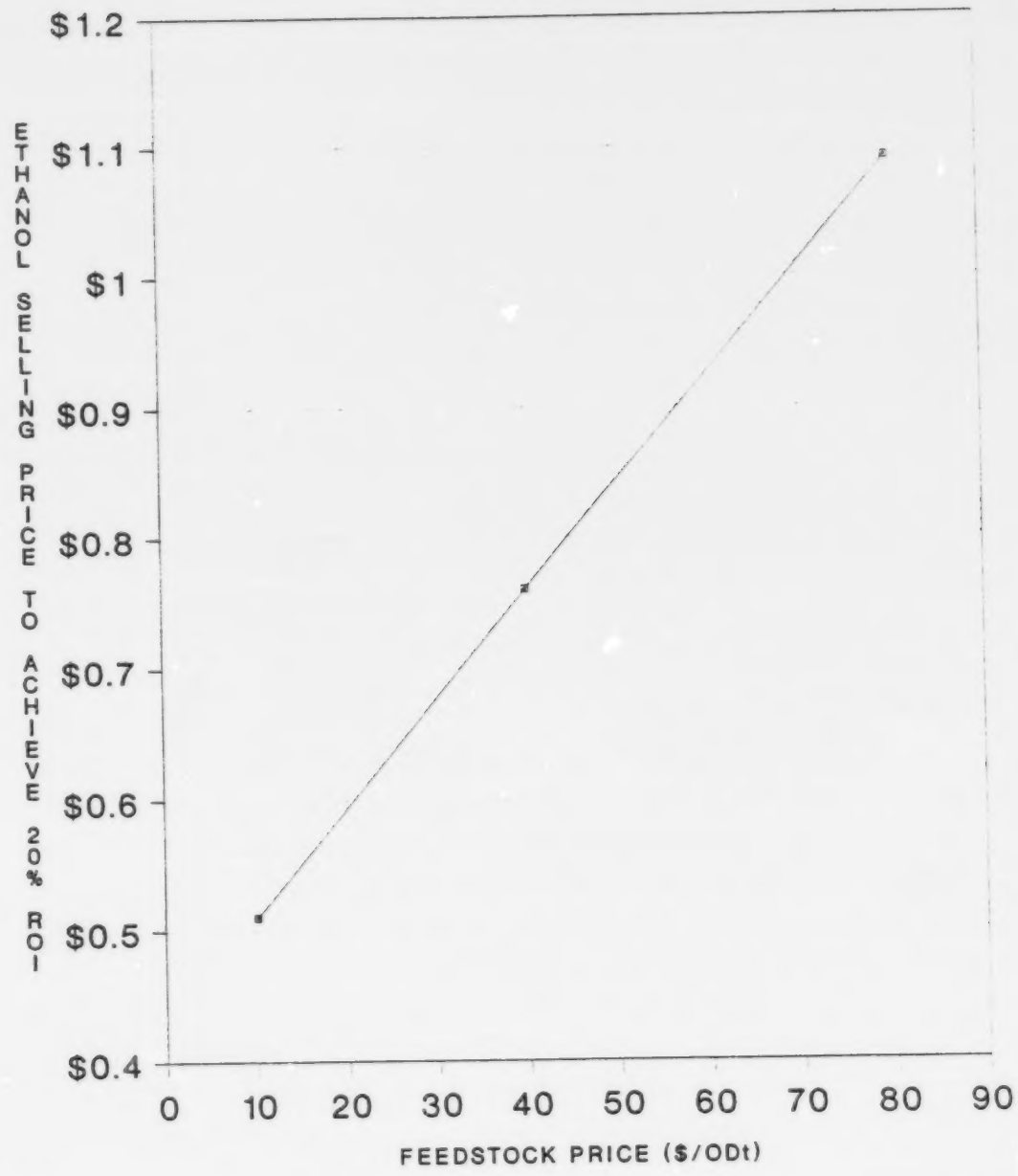

FIGURE VI-3 EFFECT OF FEEDSTOCK PRICE ON ETHANOL SELLING PRICE FOR A 25 ML/yr ACID HYDROLYSIS BASED PLANT

waste residues such as sawdust and shavings. Although pulp chips are better suited to the process, their use cannot be economically justified at this time.

(d) Variation in Capital Cost

The sensitivity of the economics to capital cost variations was analyzed. Two scenarios were investigated: base case capital cost escalated by 20% and base case deflated by 10%. Again, the ethanol selling price required to achieve a 20% ROI was determined. The results are shown in Figure VI-4.

The relationship between capital cost changes and ROI is fairly linear over the range studied, and indicates that the economics are not very sensitive to capital cost variations. The ethanol price ranges from $ 0.57/L for the high case to $ 0.48/L for the low case.

2. Enzymatic Hydrolysis Based Plant

(a) By-product Credits

By-product credits were included in the base case analysis for lignin, pentose molasses and fodder yeast. The effect of these credits is shown in Table VI-6. The estimates of by-product credits for the enzymatic case are somewhat conservative, lowering the production price by about $ 0.24/L. Despite this, the effect of the credits on profitability is marked. The ROI improves by more than 12% with the inclusion of by-product credits.

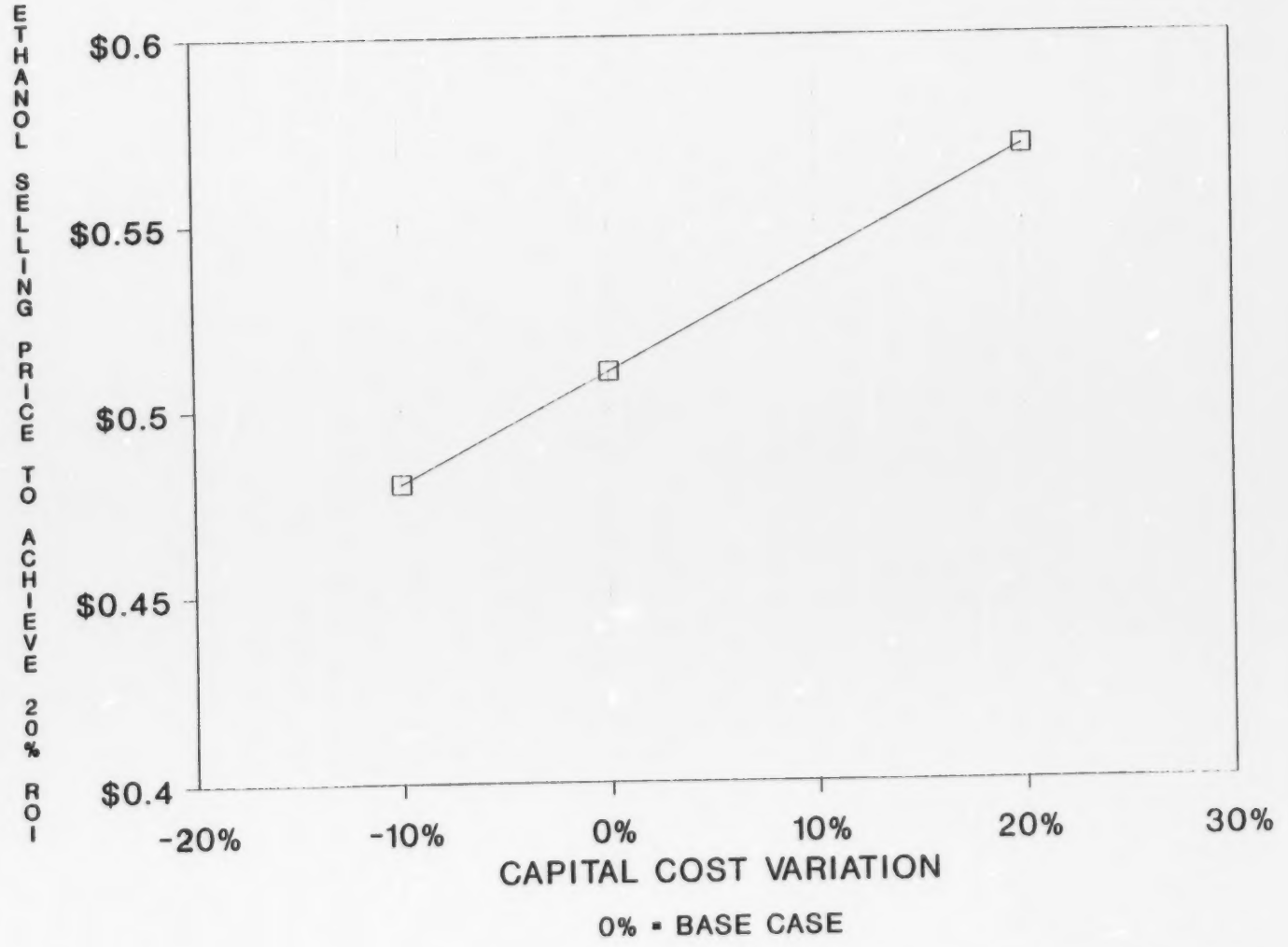

FIGURE VI-4 EFFECT OF CHANGES IN CAPITAL COST ON THE RETURN ON INVESTMENT FOR A 25 ML/yr ACID HYDROLYSIS BASED PLANT

TABLE VI-6 EFFECT OF BY-PRODUCT CREDITS ON ROI FOR AN ENZYMATIC HYDROLYSIS BASED PLANT

Ethanol production	(ML/yr)	9.6	24.0	48.0
ROI for base case	(%)	4.0	14.1	20.4
ROI for no by-product credits	(%)	0	0	6.6

Use of less conservative estimates of by-product credits could greatly improve the economics of the enzymatic process, possibly to the point where it is superior to the acid case.

The lignin by-product credit, in particular, can affect plant economics. In this study, the price of lignin used was that of lignosulphonates. Given the reactive nature of this lignin, the by-product credit could be substantially higher. An analysis was done using base case conditions except with a lignin price of $ 400/tonne, as suggested by Foody (1987). This increases the revenue from by-products by 107% compared to the base case. The return on investment for the three plants becomes:

Ethanol Production	ROI (%)
9.6 ML/yr	14
24 ML/yr	23
48 ML/yr	31

(b) Selling Price of Ethanol

As for the acid hydrolysis case, the return on investment was determined for the following selling prices of ethanol: net at $ 0.30/L, $ 0.40/L, $ 0.50/L and $ 0.70/L. The results are shown in Figure VI-5.

At the target market price of $ 0.50/L, only the largest plant, 50 million L/yr, achieves a rate of return of 20%. At $ 0.30 and $ 0.40/L, none of the three plants can be considered profitable. At $ 0.70/L, the 25 and 50 million L/yr plants exceed the hurdle rate of return of 20%.

It appears that the smallest plant cannot achieve a 20% ROI, while the medium-sized plant can only do so with an ethanol price of $ 0.70/L. Thus, for the parameters used in this study, the size of an enzymatic hydrolysis based plant needed for economic viability is somewhat larger than that for the acid hydrolysis plant.

(c) Feedstock Price

Prices of wood feedstock of $ 10/ODt, $ 40/ODt and $ 80/ODt were considered to reflect market prices of sawdust and shavings, mixed chips, sawdust and shavings, and pulp chips, respectively. The required ethanol selling price to achieve a 20% return was determined (Figure VI-6).

The results are similar to the acid hydrolysis case, indicating that the only economically viable feedstock is sawdust and shavings, or comparably priced wood residues.

(d) Variation in Capital Cost

As for the acid case, the sensitivity of the economics were examined for a 20% increase and a 10% decrease in the capital cost estimate. Again, the economics were not sensitive to the capital costs, as shown in Figure VI-7. To achieve a 20% ROI, the ethanol would have to sell for $ 0.56/L for the escalated case, and $ 0.46/L for the deflated case.

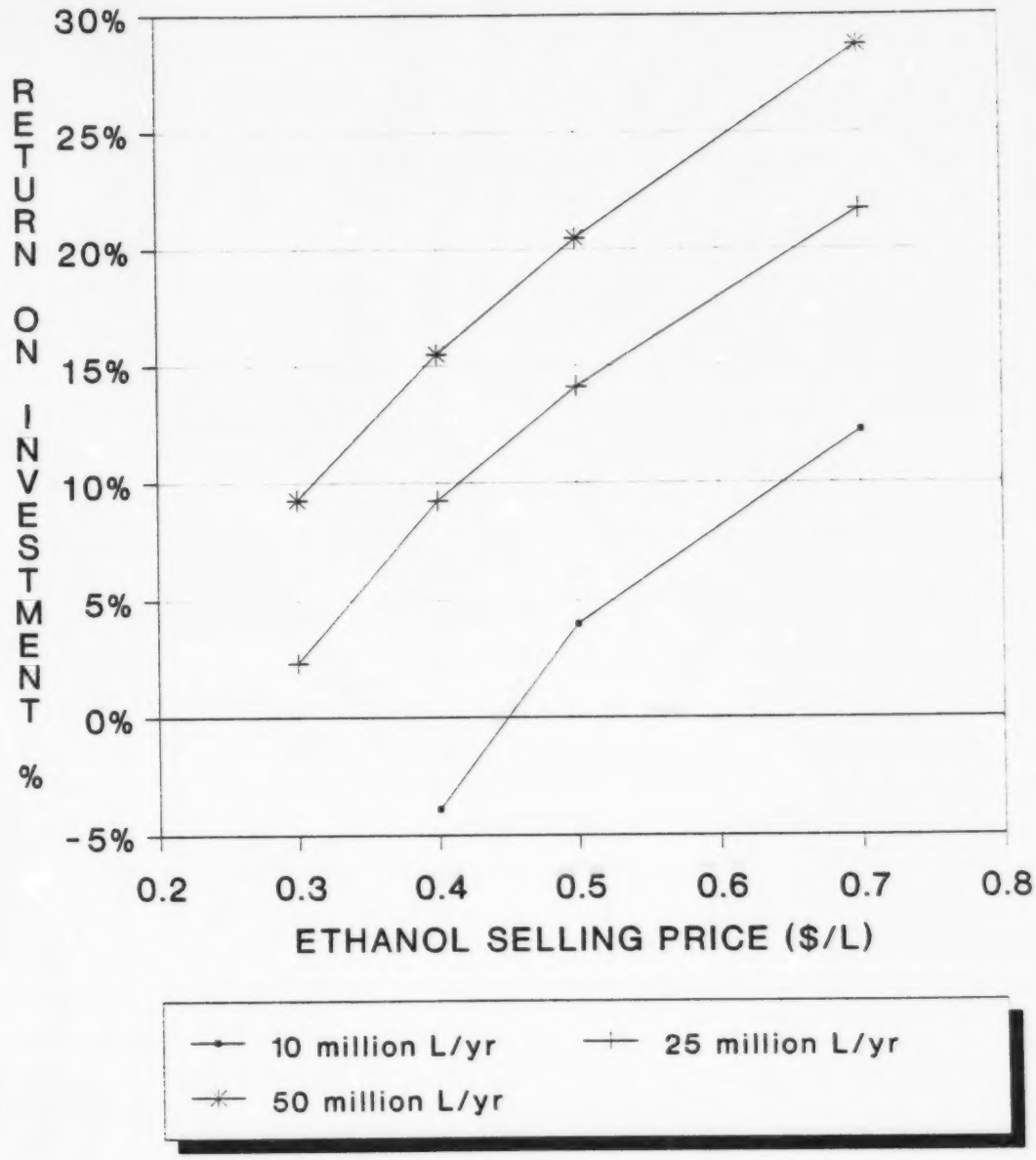

FIGURE VI-5 EFFECT OF ETHANOL SELLING PRICE ON RETURN ON INVESTMENT FOR AN ENZYMATIC HYDROLYSIS BASED PLANT

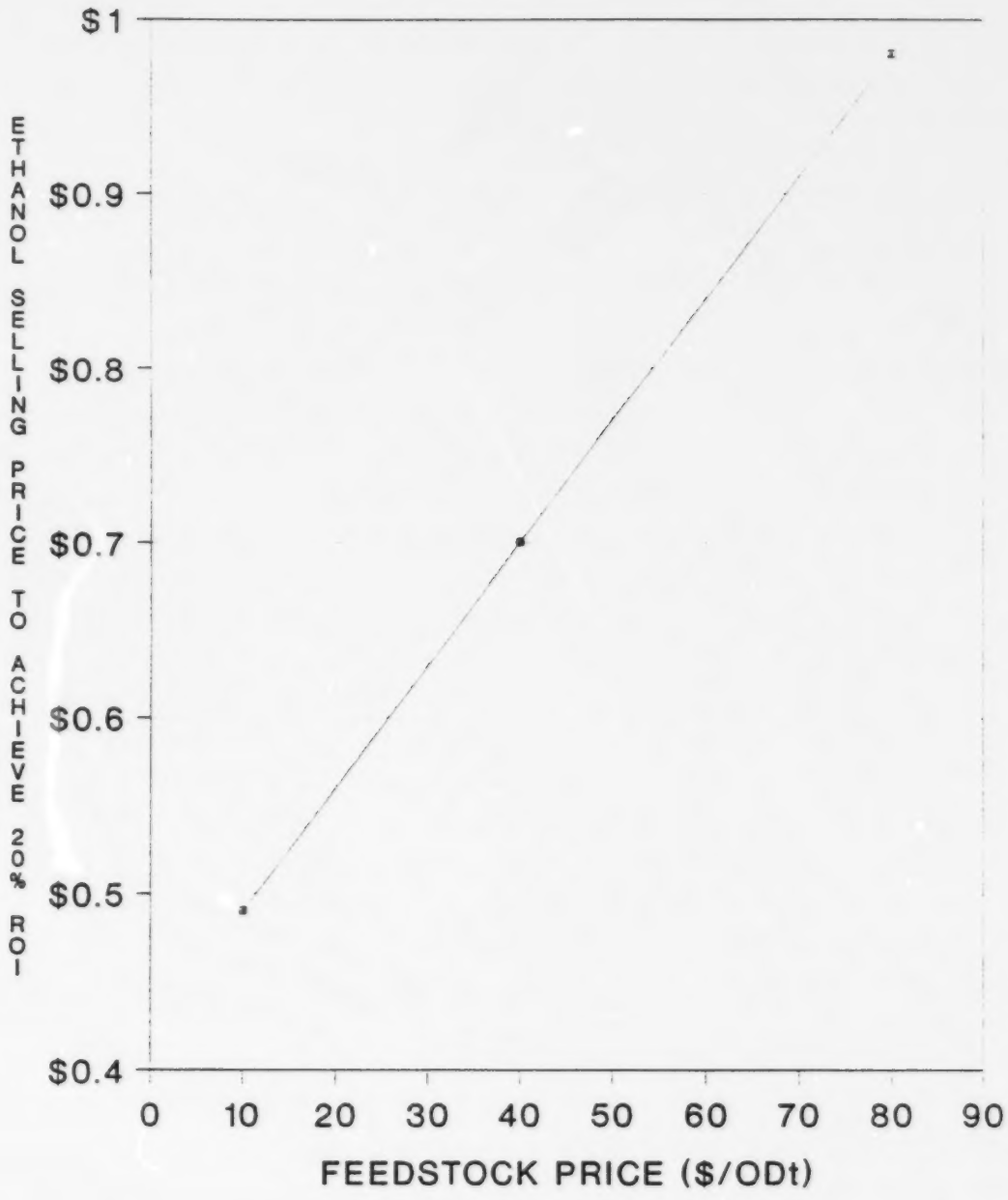

FIGURE VI-6 EFFECT OF FEEDSTOCK PRICE ON ETHANOL SELLING PRICE FOR A 25 ML/yr ENZYMATIC HYDROLYSIS BASED PLANT

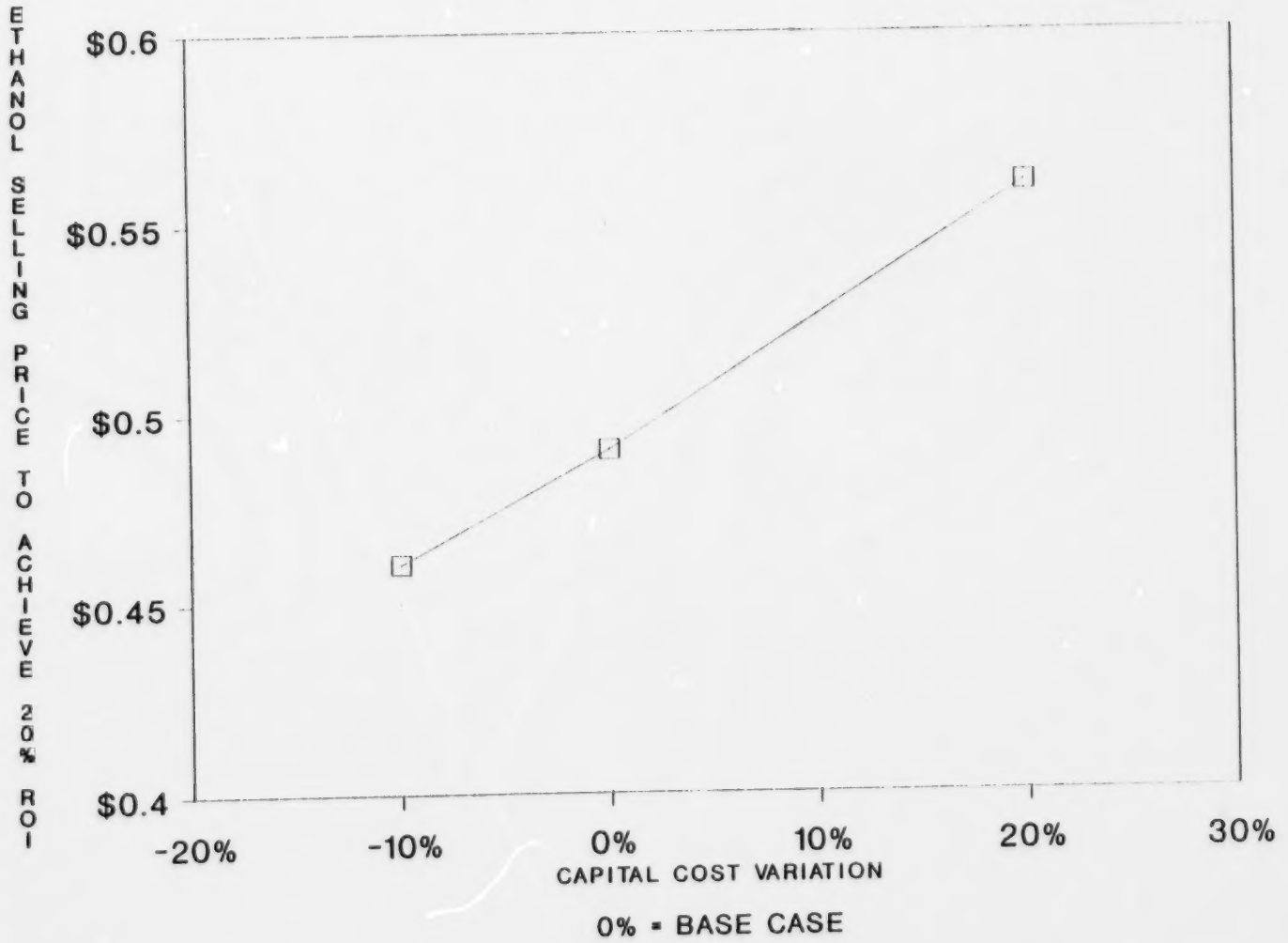

FIGURE VI-7 EFFECT OF CHANGES IN CAPITAL COST ON THE RETURN ON INVESTMENT FOR A 25 ML/yr ENZYMATIC HYDROLYSIS BASED PLANT

VII. MERITS AND DIFFICULTIES OF COUPLING AN ETHANOL PLANT AND A SAWMILL

A. Industry Input

An important part of the study was discussion with industry to explain the processes and economics of converting wood residues to ethanol and to document their views and concerns about coupling an ethanol plant to a sawmill. The focus of this survey was the interior region of British Columbia, however, a limited number of companies were also contacted in eastern Canada to provide some indication of universality of the industries' views and to identify any concerns which might be particular to the study area.

The following companies cooperated in the survey:

British Columbia

Lignum Ltd.
Weldwood of Canada Ltd.
Slocan Forest Products Ltd.
Fletcher Challenge Canada Ltd.
MacMillan Bloedel

Ontario

Abitibi Price Inc.
Carson Lake Lumber Ltd.

All of the B.C. companies contacted have sawmill operations in the interior of the Province. Some of the companies are principally lumber manufacturers, while others are fully integrated forest products companies and have operations

throughout B.C. and elsewhere. A list of the industry contacts and addresses is given in Appendix B.

A wide range of information was requested from industry contact by direct or telephone interview. This covered general information on ethanol from wood, technical and economic feasibility, marketing of ethanol and suggestions for what developments were needed to proceed with development of an ethanol plant. The guide used for the interviews is given in Appendix B for reference.

B. Operations

Discussions with industry and examination of the costs of operations indicates there are disadvantages to coupling an ethanol plant directly to a single sawmill. The main disadvantages are the substantial added complexity of the combined operation, including consideration of the fibre balance, and the differences in the training and experience needed to run the two types of plants. The most suitable arrangement appears to be a separately run ethanol plant that purchases feedstock at the lowest price from local suppliers.

Operating a separate ethanol plant has the merit of allowing both the sawmill and the ethanol plant to focus on their own target markets. In addition, corporate management is not required to have expertise in the broad range that would be needed to operate and market products for a combined operation.

The operation of an ethanol plant on wood residues from a sawmill provides some additional revenue to the mill and avoids the cost of operation of alternate disposal systems such as an incinerator. If the mill was near a pulp mill, all sawmill residues would likely be utilized at the pulp mill for boiler fuel, and so would not be available for use at the ethanol plant. The added revenue to the sawmill would be attractive, but relatively minor compared to the value of lumber.

Avoiding manpower and equipment that would otherwise be needed for alternate disposal of the wastes would be an incentive to the mill.

A potential difficulty with providing sawdust and shavings to an ethanol plant is that the remaining residues would be primarily wet bark, which, by itself, is more difficult to burn and to sell to others for fuel. This has a negative impact on an in-plant incinerator used for residue disposal, causing operating problems and worsening air emissions.

An ethanol plant would require a steady and reliable supply of feedstock, which could best be satisfied by ensuring a sufficient inventory was maintained and by having a diversity of suppliers or supply guarantees. Sawmill operations often are fairly steady, but can be interrupted for prolonged periods by labour problems or declining lumber markets.

C. Energy Considerations

Many forest products industries are in a position to self-generate their thermal energy and electrical requirements using energy systems which utilize mill residues as fuel. An ethanol plant can be thought of as an alternative energy system; while its main objective is the production of ethanol from wood residues, it can also produce steam and electricity for use by the sawmill. However, the question is whether or not a coupled ethanol plant/sawmill can be energy self-reliant or economically attractive.

The main needs for thermal energy in a sawmills are to provide kiln drying and space heating. The energy requirements for space heating are highly variable, depending on both the weather and the mill design, but is typically about 7% of the energy requirement for kiln drying (Edwards, 1987). The total thermal energy consumption is of the order of 1.6 GJ/Mfbm or 0.68 GJ/m^3 (Edwards, 1987), but this is an industrial average value, and the actual value at a plant

depends on a number of site-specific parameters. For the most part, sawmills have preferred to use natural gas over wood-fired systems because of its convenience and performance:

- natural gas is flexible to the heating requirements, allowing mills to minimize waste by using only as much gas as is necessary

- cost of steam heating is often greater than that of natural gas heating, and adds operating costs because of the requirement for steam engineers

The electrical energy requirements for B.C. sawmills range from 20 to 90 kWh/m^3 (Levelton, 1982), with an average of about 60 kWh/m^3. Again the actual values are site-specific.

Based on this data, the annual energy requirements of the typical B.C. sawmills studied are as shown in Table VII-1.

Typical costs of electricity and natural gas for larger sawmills in British Columbia are:

electricity = $0.04/kWh
natural gas = $3.00/GJ

At these prices, the cost to a 150 MMfbm/yr mill, for example, based on energy requirements shown in Table VII-I, would be $1.8 x 10^6

If the sawmill were to switch to a wood-fired co-generation scheme, the literature (Levelton and Elliott, 1983) suggests that the costs of generating the

TABLE VII-1 ANNUAL ENERGY REQUIREMENTS OF B.C. SAWMILLS

Nominal Lumber Production (MMfbm/yr)	50	100	150
(m^3/yr)	118,000	236,000	354,000
Thermal Energy Requirement (GJ/yr)	80,240	160,480	240,720
Electrical Requirement (kWh/yr)	7.08×10^6	14.16×10^6	21.24×10^6
Total Energy Requirement (GJ/yr)	105,730	211,460	317,180

energy from a wood waste energy system, exclusive of the costs of wood waste are:

electricity = $0.05/kWh
steam = $2.90/GJ

Based on these nominal values, a change to a wood-fired scheme would not reduce the cost to the sawmill for the energy required.

The ethanol plant, on the other hand, could offer to supply the sawmill with its energy needs, at the same price as the provincial utilities or lower, i.e. $1.8 x 10^6 for the large sawmill. This represents close to 6% of the annual avenue of the largest acid hydrolysis based plant ($28.09 x 10^6), which is certainly attractive.

For a coupled ethanol plant/sawmill operation then, there appears to be an economic benefit to the ethanol plant and a fairly neutral effect on the costs to the sawmill. However, there are other economic considerations:

- the energy requirements of both plants are highly variable. In particular, for sawmills the peak energy demand can be as high as 3 to 5 times the demand during normal production conditions. It would be very difficult to satisfy the energy needs of both plants without designing the system with considerable over capacity.

- for a mill to change over to a wood-fired system, it would have to undergo expensive retro-fitting of steam heating equipment to the dry kilns and removal of existing gas-fired equipment.

It appears that there would be little benefit to the sawmill, from an energy cost point of view, to operation of a coupled ethanol plant and sawmill. There would, however, be an economic benefit to the ethanol plant because of the additional

revenue generated. In general, the sawmill industry representatives contacted during the study shared this point of view, for this and other reasons.

D. Economics

The primary merit of utilizing sawmill wood residues for ethanol production is that the sawmill receives some additional revenues, though this is minor in proportion to the revenue from lumber sales. In a close-coupled ethanol plant/sawmill, there would be a minor saving of materials handling equipment compared to totally separate operations. The analysis presented earlier, indicates that close-coupling would only be practical for a very small plant of about 10 ML/yr. For larger plants, wood feedstock would have to be supplied by more than one mill, and in this case, full receiving and storage facilities for the feedstock would be needed.

Assuming sawdust and shavings are acceptable to the hydrolysis process, their use is beneficial because of low cost. Use of chips from sawmills is uneconomical because of their high value for pulp production.

The sale of by-products is important to the economics of both acid and enzymatic hydrolysis based ethanol plants. This is somewhat of a disadvantage because of the wide range of products and, consequently, the market sectors that are involved. Marketing of the output of the plant requires a distribution network for ethanol (for fuel), animal feeds (fodder yeast, pentose concentrate), resins or phenol substitutes (enzymatic hydrolysis only) and furfural (acid hydrolysis only). Ethanol is the predominant revenue source, but a plant would not be viable with ethanol sales only unless much higher yields and ethanol selling prices were achieved. Such a development would reduce dependence on revenues from the lesser by-products.

E. Environmental Impacts

In the interior of B.C., at present, there is generally a surplus of wood residues, though this is often not the case near pulp mills because of their demand for boiler fuel and some sawdust for pulp furnish. Installation of an ethanol plant in this area would consume some of the excess wood residues that are now being disposed of by landfilling or incineration, reducing pollution that results from these activities.

Ethanol plants are also sources of pollution. Air emissions occur from the boiler plant, though these would meet Provincial objectives and be much less than what would be produced by a "beehive" burner or single chamber combustor. Effluent is produced from cleaning of reactor vessels, enzyme production (enzymatic hydrolysis only), lignin dewatering (acid hydrolysis only) and other parts of the plant. This is treated in the plant prior to discharge and would meet Provincial objectives. Solid wastes are produced to a minor degree except for acid hydrolysis, which produce a calcium sulphate sludge. This waste is a disposal problem when landfilled unless special precautions are taken since it can be converted to H_2S under anaerobic conditions by sulphur reducing bacteria, creating odour and toxic leachate.

The ethanol plants considered in this study produce a pentose concentrate from the stillage for animal feed. If a market for this product cannot be developed it can be converted to biogas (methane and CO_2) for fuel in the plant or treated aerobically with other plant effluent.

F. Marketing

This study examined the advantages and disadvantages of close-coupling a sawmill and ethanol plant and of maintaining the ethanol plant as a separate operation. It is clear that the most suitable approach is to operate the ethanol

plant independently. This allows the plant's management to focus on the target market.

In the study area there is a demand for animal feeds because of the cattle industry and other farming operations and there is access to petroleum refining operations in Vancouver, Prince George and Taylor for marketing of ethanol. In the case of enzymatic hydrolysis, the lignin produced could be used as a resin substitute or extender in plywood and other composite board manufacturing operations in the area. Considering the above, it is apparent that potential market opportunities exist in the B.C. interior for products from an ethanol plant using wood feedstock. Work is needed to establish the market price for the plant's products and the size of the market that could be developed.

Discussions with industry identified a number of concerns with regard to marketing the products from the ethanol plant. The main difficulties of concern to the industry are:

- they do not have experience with marketing any of the plant's products and could not utilize their existing distribution network;

- the products have diverse markets, making marketing difficult;

- it would be best to have a company in the petroleum industry to market and distribute fuel ethanol.

G. Ethanol Production Processes

A major difficulty with both acid and enzymatic hydrolysis is that neither process is proven for softwood feedstocks of the size of sawdust and shavings. Economic results and consideration of the residues available indicate that these are the residues that should be used by the plant. Before the companies contacted would seriously consider investment in a wood-based ethanol plant, a

demonstration facility would have to be in operation. This plant is needed in industry's view to provide reliable data on process performance, plant operation, problem areas and costs.

In the long term, assuming markets could be fully developed for reactive lignin, the enzymatic hydrolysis based ethanol plant appears to offer the greatest potential for the interior of British Columbia. The process produces ethanol, animal feed and lignin, all of which have potential markets. However, the return on investment for this type of plant, with base case assumptions, is under 20% except for the 50 ML/yr plant. This changes when the lignin price is increased from $ 150/t to $ 400/t, with the return on investment for a 25 ML/yr plant increasing to 23%.

Over the short term, acid hydrolysis appears to be the more attractive process. Return on investment is higher, the plant is less complex and the status of the technology is closer to proven compared to enzymatic hydrolysis. Disposal of calcium sulphate sludge and the need for use of corrosion resistant materials are negative aspects of the technology.

VIII. CONCLUSIONS

A. Process

1. Acid hydrolysis based ethanol plants have a lower ethanol yield and lower capital and operating costs than enzymatic hydrolysis based plants:

	Acid Hydrolysis	Enzymatic Hydrolysis
Ethanol yield (L/ODt)	240	286
Capital Cost ($/Annual L)		
10 ML/yr	2.20	3.21
25 ML/yr	1.54	2.23
50 ML/yr	1.17	1.69
Operating & Maintenance Cost ($/Annual L)		
10 ML/yr	0.35	0.54
25 ML/yr	0.25	0.41
50 ML/yr	0.20	0.36
Revenues ($/Annual L)		
Ethanol	0.50	0.50
By-products	0.08	0.24

Higher yields have been projected for both processes with refinements to process design. This is especially true for enzymatic hydrolysis, because of the rapidly developing status of this process technology.

2. Neither acid hydrolysis nor enzymatic hydrolysis is proven for softwoods of the size of sawdust and shavings. This severely hampers commercial

development of ethanol plants that can use sawmill residues as feedstock because sawdust and shavings are in abundant supply in the interior of B.C. at low cost. Use of wood chips from sawmills is uneconomical. Further work is needed to allow utilization of sawdust and shavings as hydrolysis feedstock.

3. For the interior of British Columbia, enzymatic hydrolysis based ethanol production has the most commercial potential, because of the potential local markets for ethanol, animal feed and lignin based resins. In the short term, the acid hydrolysis process is preferred since it has low cost, is closer to proven technology and yields a higher return on investment.

B. Energy

Energy tie-ins between the ethanol plant and existing sawmills were concluded to be unattractive for the following reasons:

- it would be more economically and technically attractive for the sawmill to use either natural gas or its own residues for its thermal energy needs

- the variability in energy requirements at each plant make operation difficult

C. Economics

1. Acid hydrolysis based ethanol plants yield a higher return on investment than do enzymatic hydrolysis based plants under base case prices for ethanol

($ 0.50/L) and by-products:

	Return on Investment (%)	
	Acid Hydrolysis	Enzymatic Hydrolysis
Plant Capacity:		
10 ML/yr	9.5	4.0
25 ML/yr	19.6	14.1
50 ML/yr	26.9	20.4

2. The most attractive feedstocks for an ethanol plant in the interior of British Columbia are sawdust and shavings because of their availability and low cost.

3. Based on a minimum 20% return on investment, as suggested by industry, an acid hydrolysis based plant should be sized to produce 25 ML/yr or more and an enzymatic hydrolysis plant should be sized to produce 50 ML/yr or more.

4. The return on investment for the hydrolysis processes and plant sizes considered in this study are fairly sensitive to by-product prices and relatively insensitive to capital costs. This is most notable for the effect of the lignin by-product price on the economics of any enzymatic based ethanol plant. Increasing the lignin price from $ 150/tonne to $ 400/tonne (close to 50% of the phenol price) with other prices remaining the same, increases the return on investment for all plant sizes by about 10%, bringing the ROI for the 25 ML/yr plant to 23%. At this level, the ROI is higher than that for the acid hydrolysis based plant (19.6%).

D. Perspective of the Lumber Industry

The following conclusions are based on a targeted, but limited survey of the industry. They reflect the commonly expressed concerns and opinions of the industry, but special circumstances may exist at a particular sawmill site that could make some of these conclusions inappropriate.

1. Considering the potential streams and functions of personnel that could be shared in an ethanol plant/sawmill complex and the difficulties that arise with this approach, industry representatives have indicated a preference for a stand-alone ethanol plant. This plant should be sited in the proximity of one or more sawmills to minimize the cost of feedstock and should arrange long-term feedstock supply/price contracts.

2. Sawmills are interested in selling their sawdust and shavings as feedstocks for an ethanol plant, preferably at a higher price than now obtained. Removal of these residues from the total mill waste stream would leave principally wet bark. This waste would be more difficult to dispose of because of its poor combustion and handling characteristics than the original mixed hog fuel stream. In the case of landfilling, however, the volume of residues to be disposed of would be reduced.

3. A demonstration ethanol-from-wood plant is needed to address industry's concerns about performance, reliability, cost and operating requirements. The present technology is perceived to be high risk because of the uncertainty in plant economics and the process.

4. The minimum acceptable return on investment after taxes is 20 - 25%.

5. Forest products companies have expertise with marketing and distributing lumber and other building products, but would find it difficult to market ethanol

and the diverse by-products from an ethanol plant. Companies concentrating on lumber manufacturing were disinterested in the marketing of ethanol and the wide range of by-products because of a desire to concentrate on core markets. Petroleum and/or petrochemical companies were considered better positioned to market the products from an ethanol plant.

E. Environmental Impacts

1. Use of sawdust and shavings for ethanol production would eliminate air pollution caused by incineration or landfilling of these same wastes, which could be a significant improvement, especially if the residues are now burned in a beehive burner or single chamber incinerator. However, the ethanol plant would generate air emissions from its boiler plant and waste water discharge from its effluent treatment system. Calcium sulphate from an acid hydrolysis plant poses a significant disposal problem.

F. General

1. BIOSIM is an effective tool for investigating design options for the ethanol plant, but cost data needs to be updated and, in some instances, included in greater detail.

IX. RECOMMENDATIONS

1. A small portable plant should be developed to demonstrate enzymatic hydrolysis and fermentation to potential commercial developers of ethanol plants. The unit should be able to process sawmill wood residues, particularly sawdust and shavings, and should be of a size that can provide engineering data needed for a detailed feasibility study of a prototype full-scale plant. The unit need not include all parts of a complete plant, but, instead, should include only the feedstock preparation, enzymatic hydrolysis and fermentation steps.

2. Pilot studies of steam explosion pretreatment of softwood sawdust and shavings should be conducted.

3. Research and development should proceed to develop commercial products from the lignin separated by enzymatic hydrolysis of wood, with emphasis on substitute products for resins used in the production of composite wood boards.

4. Research and development should continue on the development of a yeast for xylose fermentation, to increase the overall ethanol yield.

5. Research and development of enzymatic hydrolysis of wood should include use of sawdust and shavings feedstocks. The performance of these feedstocks should be established.

6. A survey of the petroleum and petrochemical industries should be done to determine their interest in producing ethanol from wood and identify any real or perceived roadblocks to such development. A cross section of the industry should be included.

7. The recommended demonstration unit should be developed and tested in western Canada, and in order to stimulate their interest, the involvement of the forest products industry in this development program should be actively encouraged.

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APPENDIX A

EQUIPMENT SELECTIONS AND INPUT PARAMETERS

FOR EXAMPLE CASE STUDY

EXAMPLE CASE STUDY: ACID HYDROLYSIS PLANT 25 ML/yr

INPUT PARAMETER	INPUT
GENERAL	
Identification	RGQ2ACID
Energy Form to be Produced	Ethanol
Continuous Rated Ethanol Output (L/h)	2855
PROCESS EQUIPMENT	
System Option for Ethanol Production	Anhydrous
Hydrolysis Process	Acid Hydrolysis
Type of Process	Batch
Type of Fermentor	Continuous
Type of Yeast Dryer	Steam Tube Dryer
Type of Distillation Unit	Azeotropic Distillation
FEEDSTOCK DATA	
Primary Feedstock Species	Balsam Fir
Higher Heating Value (KJ/kg)	20,000
Moisture Content (wt %, wet basis)	45
Specific Heat of Dry Fuel (KJ/kg C)	1.370
Bulk Density (kg/m^3, wet volume)	235
Wood Density (OD kg/m^3, dry volume)	370

INPUT PARAMETER	INPUT
Ultimate Analysis (wt %, dry basis)	
Carbon	50.4
Hydrogen	5.9
Nitrogen	0.1
Sulphur	0.0
Oxygen	43.3
Ash	0.3
Lignin Content (wt %, dry basis)	28.54
Total Hexosan Content (wt %, dry basis)	58.4
Total Pentosan Content (wt %, dry basis)	5.15
Alcohol/Benzene Extractives Content (wt %, dry basis)	3.0
Ash Content (wt %, dry basis)	0.19
Other Constituents (wt %, dry basis)	4.74
Type of Feedstock	Sawdust/shavings
Feedstock Size	
Percent of Feedstock between 0 and 1.25 mm	4.0
Percent of Feedstock between 1.25 and 2.5 mm	6.0
Percent of Feedstock between 2.5 and 5.0 mm	20.0
Percent of Feedstock between 5 and 10 mm	47.0
Percent of Feedstock between 10 and 14 mm	19.0
Percent of Feedstock greater than 14 mm	4.0

INPUT PARAMETER	INPUT
MATERIALS HANDLING & STORAGE	
Source of Biomass Fuel	Outside plant gate
Weighing Requirement?	Yes
Weigh Scales	Truck scale - pitless
Unloading Equipment	Truck unloader
Type of Unloading Equipment	Platform truck dumper
Mobile Equipment Requirement?	Yes
Conveyor idler)	Belt conveyor (troughing
Belt Length (m)	70
Foreign Material Removal Requirement?	Yes
Ferrous Metal Removal?	Yes
Magnetic Removal	Overhead magnet
Non-Ferrous Metal, Rock and Sand Removal	Sand removal screen
Further Screening Requirement?	Yes
Screen Selection	Deck screen
Conveyor	Belt conveyor (troughing idler)
Belt Length (m)	20
Biomass Fuel Storage	Uncovered
Stacking/Reclaiming	Stationary belt - conveyor stacker

INPUT PARAMETER	INPUT
Belt Length (m)	100
Fuel Reclaiming	Reciprocating stoker reclaimer
Mobile Equipment	Rubber tired vehicle
Return Conveyor	Belt conveyor (troughing idler)
Belt Length (m)	70
Biomass Moisture Removal	None
Surge Bin Requirement?	Yes
COSTS AND ECONOMIC DATA	
Year for Costs	1988
Month for Costs	June
Chemical Engineering Plant Cost Index	342.5
Ratio of Capital Cost, Time of Estimate / Capital Cost, June 1982	1.13
Average Annual Inflation Rate Since June 1982 (%)	5
Wood Feedstock Cost ($/OD tonne)	10
Electricity Cost ($/KWh)	0.04
Cost of Water ($/KL)	0.00
Cost of Aux. Fuel ($/GJ)	4.5
Operating Hours Per Year	8400

INPUT PARAMETER	INPUT
Cost of Transportation Fuel ($/L)	0.50
Load Factor (% of Rated Capacity)	100
Cost of H_2SO_4 ($/tonne)	150
Cost of CaO ($/tonne)	100
Cost of Diammonium Phosphate ($/tonne)	470
Cost of Urea ($/tonne)	340

APPENDIX B

LIST OF CONTACTS

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Mr. John Sanderson, P.Eng. Engineering Services	MacMillan Bloedel 1075 West Georgia Street Vancouver, B.C. V6E 3R9	(604) 661-8000
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INTERVIEW GUIDELINE

GENERAL

1. What is currently being done with wood residues such as off-specification chips, sawdust and shavings in your mill? Do you feel that some of this material is underutilized?

2. Have you considered any alternative uses for these wood residues? What alternative uses have you considered?

3. Are you interested in producing ethanol from wood?

4. Have you looked into any of the various processes for producing ethanol from wood?

5. Why do you feel that there has been so little interest to date in ethanol plant/forest products mills combinations in B.C.?

FEASIBILITY

What size of ethanol plant would be of interest to you:

(a) One that is sized to use only the mill residues such as sawdust and shavings; or

(b) A larger plant using chips as well as waste residues, allowing you to benefit from economies of scale.

Economic Feasibility

(a) What is your decision on whether or not you would implement an ethanol plant based on (i.e., is it economic (ROI) or non-economic (environmental, technological, etc.))?

(b) A survey of the various research which has been done places the cost of producing ethanol from wood to be somewhere between $ 1.00/litre and $ 0.40/litre. Ethanol is currently marketable at about $ 0.50/litre as a fuel additive. At what cost would the process become attractive to you?

Technical Feasibility

(a) Do you feel that the coupling of an ethanol plant to a sawmill is feasible, from a technical standpoint alone?

(b) Keeping in mind the following points about the two processes,

Acid Hydrolysis
- proven technology
- lower sugar yields, corrosion problems, and expensive acid-resistant equipment
- non-reactive lignin by-product useful only as fuel

Enzymatic Hydrolysis
- not yet proven, but with the potential for higher conversion of cellulose
- expensive pretreatment, slower production rates
- more useful by-products

which process do you feel is more suitable for your mill, and give reasons for this choice.

(c) Do you have any technological concerns about either process, i.e., any potential problem areas in the plant?

MARKETING

1. The main product would be ethanol. The market for it includes use:

   - as a fuel additive (e.g., Mohawk is currently marketing ethanol-blended gasolines);
   - as a commercial-grade product;
   - in industrial solvent applications.

   Would you be able to establish a market for ethanol?

2. Both processes produce lignin as a by-product. Would you:

   (a) Burn it as a fuel;

   (b) Market it if possible.

   The lignin from enzymatic hydrolysis processes is in reactive form and could be used as a replacement for phenol for making resins and adhesives, possibly for plywood manufacture.

3. Both processes produce unfermented pentose sugars. The two possible uses for this are:

   - concentration to form pentose molasses, which could be used as an animal feed additive. As well, the enzymatic process produces a protein-rich feed by-product, which is saleable as animal fodder;

- process them (by anaerobic digestion) to a gas consisting mainly of methane, which could be used as a fuel gas.

Which products are of more interest for market and revenue reasons?

OPERATIONAL CONSIDERATIONS

1. What are some of the operational requirements which you would have to consider, regarding hiring and training of staff?

2. Any sharing of equipment or utilities could help to reduce costs. Do you have any equipment or utilities which could be shared by both the ethanol plant and the sawmill? This is likely to include equipment for materials handling storage, and drying.

3. For utilities, do you produce any excess steam or electricity, or solid fuels for use in boilers?

4. Given that your operations can be seasonal, would you consider continuing ethanol plant operation when the mill is shut-in? Would you have enough of a stockpile of residues, or would you purchase additional residues.

CLOSING

1. What further work would you like to see done before you would seriously consider an ethanol plant?

2. The next phase of the work includes a more detailed design study and cost analysis, and identification of the optimum type and size of ethanol plant, possibly for a specific mill. Would you be interested in cooperating in this next phase?